DURABILITY EVALUATION AND PRODUCTION OF MANUFACTURED AGGREGATES FROM COAL COMBUSTION BY-PRODUCTS

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ABSTRACT

Under the cooperative agreement with DOE, the Research and Development Department of CONSOL Energy (CONSOL R&D), teamed with Universal Aggregates, LLC, to conduct a systematic study of the durability of aggregates manufactured using a variety of flue gas desulfurization (FGD), fluidized-bed combustion (FBC) and fly ash specimens with different chemical and physical properties and under different freeze/thaw, wet/dry and long-term natural weathering conditions. The objectives of the study are to establish the relationships among the durability and characteristics of FGD material, FBC ash and fly ash, and to identify the causes of durability problems, and, ultimately, to increase the utilization of FGD material, FBC ash and fly ash as a construction material. Manufactured aggregates made from FGD material, FBC ash and fly ash, and products made from those manufactured aggregates were used in the study. The project is divided into the following activities: sample collection and characterization; characterization and preparation of manufactured aggregates; determination of durability characteristics of manufactured aggregates; preparation and determination of durability characteristics of manufactured aggregate products; and data evaluation and reporting.

LIST OF ACRONYMS

AASHTO – American Association of State Highway and Transportation Officials
AEP – American Electric Power
ASTM – ASTM International (formerly American Society for Testing and Materials)
CBR – California bearing resistance
CCB – coal combustion by-product
CCP – coal combustion product (same as CCB)
FBC – fluidized-bed combustion/combustor
FGD – flue gas desulfurization
GPCO – Georgia Power Company
JEA – Jacksonville Electric Authority
LOI – loss on iginition
OCDO – Ohio Coal Development Office
PTM – Pennsylvania testing method
PG&E – Pacific Gas & Electric Company
SDA – spray dryer ash/absorber
SEM – scanning electron microscope/microscopy
SSD – saturated-surface-dry
TGA – thermogravimetric analysis
TNP – Texas-New Mexico Power Company
XRD – X-ray diffraction

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INTRODUCTION

FGD material, FBC ash and fly ash have useful engineering properties that make them attractive for high-volume use in construction. However, only about 19% of the FGD material produced in the United State is utilized. About 70% of utilized FGD material is production of gypsum from forced-oxidation wet scrubber systems for wallboard production. The wallboard market for gypsum is near saturation. Fly ash is the most utilized coal combustion by-product. Installation of NOx control technology (low NOx burners and SCR) can affect the utilization of fly ash. Many factors impede the utilization of FGD material and fly ash. One major concern for construction-related utilization is the durability. FBC ash and some dry FGD by-products were reported to have expansive properties, which cause durability problems in utilization. In contrast, FGD sludge, fixated with fly ash and lime, has been used commercially in road construction, flowable fill and structural fill for years. FGD material includes dry FGD by-product and fixated FGD sludge; FBC ash is often considered as an FGD material. FGD material and FBC ash generated from different processes have distinctly different characteristics. Installation of low NOx burners for NOx control often increases fly ash LOI that causes durability problems for use of fly ash in concrete production. Therefore, it is important to conduct a systematic study of the durability using a variety of FGD and fly ash specimens with different chemical and physical properties and under different freeze/thaw, wet/dry and long-term natural weathering conditions. The objectives of the study are to establish the relationships among durability and characteristics of FGD material, FBC ash and fly ash, to identify the causes of durability problems and, ultimately, to increase the utilization of FGD material, FBC ash and fly ash as a construction material. Manufactured aggregates made from FGD material, FBC ash and fly ash, and products made from manufactured aggregates were used in the study.

Manufactured aggregates and products made from manufactured aggregates are suitable for use in the durability study. Manufactured aggregates usually are small with a diameter of less than 1". The effects of freeze/thaw, wet/dry, and long-term natural weathering on physical properties and structural integrity are relatively easy to identify and correlate with chemical and mineralogical changes in the manufactured aggregates. The results of this study will be generally applicable to the durability issues for the high volume use of coal combustion by-products (FGD material, fly ash and FBC ash) in construction application. In addition, the effects of mix components and preparation method on the durability can be readily evaluated with manufactured aggregates.

Production of manufactured aggregate has potential to substantially expand markets for the utilization of FGD material, FBC ash and fly ash. It could also be a cost effective way for preventing and reducing utilization problems associated with implementation of NOx control technologies at power plants. As a partial replacement of natural aggregate, the consumption of manufactured aggregate is not limited by market volume, seasonal demand, problems in handling, transportation and storage as many other utilization options (e. g., structural fill).

EXECUTIVE SUMMARY

This study is divided into four main tasks: 1) sample collection and characterization; 2) preparation and characterization of manufactured aggregates; 3) determination of durability characteristics of manufactured aggregates; and 4) preparation and determination of durability characteristics of manufactured aggregate products. The summary and conclusions of each of these follow.

Sample Collection and Characterization

Coal combustion by-products (CCBs) used in this study were collected from different utility power plants. The CCBs are divided into lime and limestone wet FGD materials, FBC ash, pulverized coal fly ash and spray dryer ash. The types of CCBs and sources of the CCBs are listed below:

Limestone wet FGD

1. Limestone wet FGD fixated with Class C fly ash
   Reliant Energy Limestone Station in Texas
2. Limestone wet FGD fixated with Class F fly ash
   Lakeland McIntosh Station in Florida

Lime Wet FGD

3. Lime wet FGD fixated with high LOI fly ash
   Reliant Energy Elrama Station in Pennsylvania
4. Lime wet FGD fixated with low LOI fly ash AEP Gavin Station in Ohio
5. Lime wet FGD fixated with high and low fly ash
   AEP Conesville Station in Ohio

FBC Ash

6. FBC ash from low-sulfur coal and lignite
   New Mexico Power TNP One Station in Texas (low-sulfur lignite)
   AES Guayama Station in Puerto Rico (low-sulfur coal)
   Tractebel Power Red Hills Station in Mississippi (low-sulfur lignite)
7. FBC ash from high-sulfur coal and petcoke
   JEA NorthsideStation in Florida
8. FBC ash from waste coal (or gob)
   PG&E Northampton Station in Pennsylvania

Pulverized Coal Fly Ash

9. Class C fly ash
   GPCO Scherer Station in Georgia
10. Class F fly ash
   JEA Seminole Station in Florida
   First Energy Sammis Station in Pennsylvania

Spray Dryer ash

11. Spray dryer ash with Class F fly ash
   Birchwood Power Station in Virginia

12. Spray dryer ash with Class C fly ash
    Sunflower Power Holocomb Station in Kansas

All CCBs were characterized for moisture contents, ultimate analyses and major elemental composition. Relevant chemical compositions and physical properties including LOI (loss on ignition), sulfur forms, solid concentration, specific gravity, lime index, and particle size distribution were also characterized for comparison.

Preparation and Characteristics of Manufactured Aggregates

Manufactured aggregates were produced with the above CCBs as feed materials in a three-step process consisting of mixing, agglomerating (pelletizing or extruding) and curing. As shown in Table A, manufactured aggregates produced from different feed materials are separated into lightweight aggregates and road aggregates. Lightweight aggregates include those produced from limestone wet FGD (fixated with Class F fly ash), lime wet FGD (fixated with high LOI fly ash and with low and high LOI fly ash), FBC ash (from low-sulfur coal, high-sulfur coal/petcoke and waste coal) and spray dryer ash (with Class F fly ash). Lightweight aggregates have maximum dry unit weights of 65 lb/ft^3 (ASTM C331 lightweight aggregate specification)) and have potential for use in production of lightweight or medium-weight concrete masonry units (CMU). Road aggregates include those produced from limestone wet FGD (fixated with Class C fly ash), lime wet FGD (fixated with low LOI fly ash), fly ash (Class C and Class F) and spray dryer ash (with Class C fly ash). Road aggregates have dry unit weights of 65 lb/ft^3 or higher and have potential for use in highway construction. Several lightweight aggregates listed in Table A were produced in the pilot plant and used in CMU block plant production demonstration. The lightweight aggregates include those made from limestone wet FGD material (fixated with Class F fly ash), lime wet FGD material (fixated with low and high LOI fly ash) and spray dryer ash (with Class F fly ash). Road aggregate made from lime wet FGD material (fixated with low LOI fly ash) was produced from the pilot plant and used in highway construction demonstration. These demonstration projects are discussed below in the Section, entitled "Summary of Related Work". Selected aggregates with different properties were used in the determination of durability characteristics of manufactured aggregates. Test specimens of aggregate products from the demonstration projects were used in the determination of durability characteristics of manufactured aggregate products.

Determination of Durability Characteristics of Manufactured Aggregates

Selected aggregates produced above were used in the determination of durability characteristics of manufactured aggregates. The selected aggregates include those produced from limestone wet FGD materials (fixated with Class C and Class F fly ash), lime wet FGD materials (fixated with low and high LOI fly ash), FBC ash (from low-sulfur coal and from high-sulfur coal/petcoke) and spray dryer ash (with Class C and Class F fly ash). The swelling properties upon wetting and the effects of natural weathering and freeze/thaw cycles treatments on properties of manufactured aggregates were determined for comparison. The swelling properties and durability comparison of aggregates are summarized in Table A. Test results are discussed below.

1. Road aggregate made from fixated wet FGD material with Class C fly ash is more durable than lightweight aggregate made with Class F fly ash, based on freeze/thaw cycles treatments. The higher durability could be related to reactivity of Class C fly ash and higher unit weight (or density) of the aggregate. High durability, especially freeze/thaw resistance, is more important for road aggregate in highway application than for lightweight aggregate in CMU application.

2. Lightweight Aggregate made with FBC ash from low-sulfur coal is more durable than that made with FBC ash from a blend of high-sulfur coal and petcoke, based on the natural weathering study. The poor durability of high-sulfur FBC ash could be related to continuous slow hydration of quick lime and anhydrite in the ash upon wetting. Addition of pulverized coal fly ash can improve durability of aggregate made with FBC ash from high-sulfur coal and petcoke.

3. Durability of aggregate made from spray dryer ash with Class C fly ash can be improved with increase in mix time, based on the natural weathering study. The improvement could be related to increased hydration of quick lime, anhydrite and others with increase in mix time.

4. Aggregate made from spray dryer ash with Class F fly ash had good durability based on freeze/thaw cycles treatment. Addition of cement did not improve aggregate durability.

5. Aggregates, made from limestone wet FGD material (fixated with Class F fly ash), FBC ash (from low-sulfur coal) and spray dryer ash (with Class F fly ash), had little swelling upon wetting. In comparison, aggregate made from FBC ash (from a blend of high-sulfur coal and coke) had high swelling upon wetting. The high swelling is related to the continuous hydration of quick lime and anhydrite upon wetting. Both hydration reactions can cause expansion (or swelling).

Table A. Properties and Durability Characteristics of Manufactured Aggregates

Feed Materials for Aggregate Production	Lightweight Aggregate	Road Aggregate
Limestone Wet FGD		
Fixated with Class C fly ash		× (a)
Fixated with Class F fly ash	× (b)	
Lime Wet FGD		
Fixated with low LOI fly ash		× (a)
Fixated with high LOI fly ash	×	
Fixated with low and high LOI fly ash	×	
FBC Ash		
Low-sulfur coals	× (b)	
High-sulfur coal/petcoke	× (c)(d)	
Waste coal (gob)	×	
Fly Ash		
Class C fly ash		×
Class F fly ash		×
Spray Dryer Ash		
With Class C fly ash		× (e)
With Class F fly ash	× (f)(b)	

(a) Aggregate with higher durability and crush strength
(b) Aggregate with little swell upon wetting
(c) Aggregate with high swell upon wetting
(d) Aggregate with lower durability and higher crush strength. Durability improved with pulverized coal fly ash addition
(e) Aggregate with higher crush strength. Durability improved with increasing mix time
(f) Aggregate with good durability with and without cement addition

Durability Characteristics of Manufactured Aggregate Products

Test specimens were prepared from concrete masonry units (CMU), cement concrete and asphalt concrete for the durability study. CMU were made with manufactured lightweight aggregates from limestone wet FGD material (fixated with Class F fly ash), lime wet FGD material (fixated with low and high LOI Class F fly ash) and spray dryer ash (with Class F fly ash) in field demonstrations. Cement concrete was made with manufactured lightweight aggregate from lime wet FGD material (fixated with low and high LOI Class F fly ash) in the qualification test for use in lightweight structural concrete. Asphalt concrete was made with road aggregate from lime wet FGD material (fixated with low LOI fly ash) in a field demonstration. The effects of wet/dry and freeze/thaw treatments on properties of test specimens were determined by monitoring dimension (length, width and height) and weight changes upon treatments. The comparison of durability characteristics is summarized in Table B. "High", "medium," and "low" listed in the table represent different levels of wet/dry and freeze/thaw resistance. Test results are discussed below.

1. CMU and cement concrete test specimens made with manufactured lightweight aggregates all had high wet/dry resistance after 50 cycles of treatments. Little dimension and weight changes were observed during treatments. The test specimens were immersed in water during the wet cycle treatment. This simulated the extreme conditions of wet/dry cycles in applications of CMU and cement concrete.

2. CMU test specimens made with manufactured lightweight aggregates from either limestone wet FGD materials or spray dryer ash had high freeze/thaw resistance after 50 cycles of treatments. In comparison, CMU made with manufactured lightweight aggregate from lime wet FGD materials had medium freeze/thaw resistance. Both cement and asphalt concrete test specimens made with manufactured aggregates from lime wet FGD materials had high freeze/thaw resistance. The test specimens were in saturated-surface-dry (SSD) conditions, but not immersed in water. This simulated the natural conditions of freeze/thaw cycles in most application of CMU and cement concrete in construction.

3. CMU test specimens made with manufactured lightweight aggregates from either limestone wet FGD materials or spray dryer ash had medium freeze/thaw resistance after 20 cycles of treatments. Test specimens made with aggregates from lime wet FGD materials were degraded after 20 cycles of treatment. In comparison, asphalt concrete made with manufactured road aggregate from lime wet FGD material had high freeze/thaw resistance after 200 cycles of treatment. Test specimens were immersed in water during freeze/thaw treatments. Test results indicate that immersion in water had a profound effect on the freeze/thaw resistance of CMU made with manufactured lightweight aggregate. Mix designs for aggregate and aggregate products production need to be modified, if simultaneous freeze/thaw cycles at extremely low temperature and water immersion cannot be avoided in the application.

Table B. Durability Characteristics of Manufactured Aggregate Products

Test Specimens	Wet/Dry Treatment	Freeze/Thaw Treatment (SSD)	Freeze/Thaw Treatment (Immersion in water)
<u>Concrete Masonry Units</u>			
Limestone wet FGD Aggregate (Fixated with Class F fly ash)	High	High	Medium
Lime wet FGD aggregate (Fixated with low and high LOI fly ash)	High	Medium	Low
Spray dryer ash aggregate (With Class F fly ash)	High	High	Medium
<u>Cement Concrete</u>			
Lime wet FGD aggregate (Fixated with low and high LOI fly ash)	High	High	(a)
Asphalt Concrete			
Lime wet FGD aggregate (Fixated with low LOI fly ash)	(a)	(a)	High

(a) Not determined

SUMMARY OF RELATED WORKS

Large quantities of lightweight aggregates and road aggregates were produced at the pilot-plant or bench-scale and these materials were used in field demonstrations with commercial equipment. Lightweight aggregates were used for concrete masonry units (CMU) production at commercial concrete block plants and in qualification tests for use as lightweight structural concrete. Road aggregates were used in asphalt concrete pavement construction. Test specimens from CMU, cement concrete and asphalt concrete were used in this study for the determination of durability characteristics of manufactured aggregate products. Certain related works conducted by the author of this report, which are relevant to this study, are summarized below in accordance with published reports. These works were conducted with partial funding from the Department of Energy (DOE) and the Ohio Coal Development Office (OCDO). The three cited reports, in addition to this report, provide an extensive body of experience in manufacturing aggregates from coal combustion by-products (CCBs).

1. McCoy, D.C., Wu, M. M, "Demonstration of the Production of Manufactured Aggregates from AEP Gavin and Conesville Station FGD Sludge", OCDO Final Report, Grant Agreement No. CDO/D-98-17, May 31, 2003.

About 25 tons of lightweight aggregate was produced from lime wet FGD material fixated with a blend of low and high LOI fly ash in pilot plant operation. FGD sludge and low LOI fly ash were collected from the AEP Conesville Station. High LOI fly ash was collected from the FirstEnergy Sammis Station. The manufactured lightweight aggregate was used in block plants for CMU production and in qualification tests for use in lightweight structural concrete. The lightweight concrete blocks and structural concrete specimens made with wet FGD manufactured aggregate met all ASTM C-90 specifications for load-bearing concrete masonry units and all ASTM C-330 specifications for lightweight structural concrete, except for drying shrinkage. Drying shrinkage could be caused by manufactured aggregate alone or by interaction of manufactured aggregate and other concrete block components (e. g., cement) during wet/dry treatment. The effects of these factors on durability characteristics of aggregate and aggregate products are included in this cited study.

2. Wu, M. M., McCoy, D. C., "Aggregate Production from Lime Wet FGD Sludge", OCDO Final Report, Grant Agreement No. CDO/D-95-2, October, 2003

About 2.5 tons of road aggregate was produced from lime wet FGD material fixated with low LOI fly ash (AEP Gavin Station in Ohio) and with cement addition in a semi-continuous bench-scale unit. The road aggregate met AASHTO M283 specifications for Class A aggregate in highway construction. An asphalt concrete pavement (72' x 11' x 1.5') was constructed using crushed manufactured aggregate (No. 8 size) as half of the coarse aggregate in the surface wearing course in Warren, Ohio in October 1998. Core samples were collected and used in the aggregate products durability evaluation.

3. Wu, M. M., McCoy, D. C., Scandrol, R. O., Fenger, M. L., Withum, J. A., Statnick, R. M., “Production of Construction Aggregates from Flue Gas Desulfurization Sludge”, DOE Final Report, Cooperative Agreement No. DE-FC26-98FT40027, May 2000.

About 72 tons of road aggregate was produced from lime wet FGD material fixated with a low LOI fly ash and with cement addition in a pilot plant operation. FGD sludge was collected from the Reliant Energy Elrama Station in Pennsylvania. The low LOI fly ash was collected from the Allegheny Power Hatfield’s Ferry Station in Pennsylvania. The road aggregates produced met AASHTO M283 specifications for use as Class A aggregate in highway construction. Two asphalt concrete pavements (350’ x 12’ x 1.5’ and 400’ x 12’ x 1.5’) were constructed using crushed manufactured aggregates (No. 8 size) as half of the coarse aggregates in the surface wearing courses in South Park, Pennsylvania, and in Nokomis, Florida. Core samples were collected and used in the aggregate products durability evaluation.

EXPERIMENTAL

Preparation of Manufactured Aggregates

Manufactured aggregates were produced in a three-step process consisting of mixing, disk pelletizing and curing. Various feed components for a specific mix design were mixed in a Littleford Brothers FM-50 mixer (Model KM-300-D) to produce a consistent mixed material for pelletization. The disk pelletization was conducted by adding the mixed material to a Ferro-Tech Inc. disk pelletizer (36" diameter Model 036 or 16" diameter Model 016) at a feed rate of about 13.4 lb/min for agglomeration. The pelletization time is about 20 to 25 minutes. The pelletized products were then mixed with embedding material and placed in the 55-gallon heated vessel for curing. The blended products were cured at about 160 °F to 170 °F and 90 to 100% relative humidity for 24 hr. About 100 lb to 200 lb of the aggregate was produced for the determination of aggregate properties including crush strength, LA abrasion, unit weight, soundness, or particle size distribution. The crush strength was determined with uncrushed aggregates with a Soiltest compressive strength machine. The aggregate crush strength reported is the average of ten measurements on ca. 1/2"x3/8" pellets (uncrushed). The LA abrasion index, unit weight, soundness index and particle size distribution were determined with crushed aggregates in accordance with the standard ASTM procedures. In addition to disk pelletization, several agglomeration runs were conducted with extrusion using a Van Ho extruder (Model NL-320) to produce green extruded products for curing. The extruded products were cured in the same conditions as those produced from disk pelletization runs.

Other Methods

Additional experimental details appear in the Results and Discussion section, where appropriate.

RESULTS AND DISCUSSION

Sample Collections and Characterization

The objectives of this task are to collect and characterize coal combustion by-products (CCBs) samples with different chemical compositions. These materials will be used to prepare manufactured aggregates in the next task. The CCBs samples include limestone wet flue gas desulfurization (FGD) sludge fixated with Class F and Class C fly ash, lime wet FGD sludge fixated with high loss on ignition (LOI) and low LOI fly ash, fluidized bed combustion (FBC) ash generated from combustion of low and high-sulfur coals, Class F and Class C pulverized coal fly ash, and spray dryer ash containing Class F and Class C fly ash.

Limestone wet FGD filter cake; Class F and C fly ash for use in fixation were collected from Lakeland McIntosh Station in Florida (Sample No. FGD-LS-FS) and Reliant Energy Limestone Station in Texas (Sample No. FGD-LS-TS). Lime wet FGD filter cake and high LOI fly ash for use in fixation were collected from Reliant Energy Elrama Station in Pennsylvania (Sample No. FGD-LM-PS). Lime wet FGD filter cake and low LOI fly ash for use in fixation were collected from AEP Galvin and Conesville Stations in Ohio (Samples Nos. FGD-LM-OS-1 and FGD-LM-OS-2), respectively. FBC ash samples generated from combustion of low-sulfur coals were collected from New Mexico Power TNP One Station in Texas (Sample No. FBC-TS) and AES Guayama Station in Puerto Rico (Sample No. FBC-PR). FBC ash generated from combustion of a blend of high-sulfur coal and petroleum coke (30/70) was collected from JEA Northside Station in Florida (Sample No. FBC-FS). In addition, FBC ash samples generated from combustion of low-sulfur lignite and waste coal (or gob) was collected from Tractebel Power Red Hill Station in Mississippi (Sample No. FBS-MS) and PG&E Northampton Station in Pennsylvania (Sample No. FBC-PS), respectively. Class C and Class F fly ash were collected from GPCO Scherer Station in Georgia (Sample No. FY-GS) and JEA Seminole Station in Florida (Sample No. FY-FS). Spray dryer ash containing Class F and C fly ash were collected from Birchwood Power Facilities in Virginia (Samples No. SDA-VS) and Sunflower Power Holcomb Station in Kansas (Sample No. SDA-KS).

The characterization results are shown below in Tables 1-A, 1-B, 1-C-1, 1-C-2, 1-D, and 1-E in accordance with types of CCBs (i.e., wet limestone and lime FGD materials, FBC ash, fly ash and spray dryer ash). The tables include moisture content, ultimate analyses and major elements. In addition, the tables include available data of LOI (loss on ignition), sulfur forms, solids concentration, specific gravity, lime index, and particle size distribution.

Table 1-A. Analyses of Limestone Wet FGD Materials

	Reliant Energy Limestone Station (FGD-LS-TS)		Lakeland McIntosh Station (FGD-LS-FS)	
	FGD Filter Cake	Fly Ash (Class C)	FGD Filter Cake	Fly Ash (Class F)
Moisture, wt% (as rec.)	35.5 (a)	0.08	49.0 (b)	0.44
Ultimate Analysis, wt%(dry)				
Carbon	0.77	0.33	1.22	5.64
Hydrogen	0.45	0.00	0.66	0.07
Nitrogen	<0.01	<0.01	0.03	0.05
Sulfur (total)	21.60	0.51	20.39	0.48
Ash (750 EC)	93.66	99.54	95.64	93.26
Major Element, wt% (dry)				
SiO_2	0.33	43.23	3.61	48.87
Al_2O_3	0.10	18.72	0.35	22.33
TiO_2	0.01	1.25	<0.00	1.33
Fe_2O_3	0.11	5.22	0.24	10.12
CaO	39.18	22.16	43.25	2.59
MgO	0.38	4.87	0.73	0.93
Na_2O	0.16	1.38	0.12	0.88
K_2O	0.03	0.47	0.10	2.09
P_2O_5	0.00	0.71	0.04	0.30
SO_3	54.01	1.28	50.64	1.20
LOI	----	0.46	-----	6.74
Specific gravity	----	2.603	2.418	2.191
Particle Size Distribution, µm				
Mean diameter	----	----	18.2	23.3
Diameter below with 90% sample lie	----	----	36.8	59.0
Diameter below with 50% sample lie	----	----	14.3	13.8
Diameter below with 10% sample lie	----	----	4.8	4.7

(a) Solids concentration of 64.5%
(b) Solids concentration of 51.0%

Table 1-B. Analyses of Lime Wet FGD Materials

	Reliant Energy Elrama Station (FGD-LM-PS)		AEP Gavin Station (FGD-LM-OS-1)		AEP Conesville Station (FGD-LM-OS-2)	
	FGD Filter Cake	Fly Ash	FGD Filter Cake	Fly Ash	FGD Filter Cake	Fly Ash
Moisture, wt% (as rec.)	46.0(a)	0.27	55.1(b)	0.05	58.6 (c)	0.17
Ultimate Analysis, wt%(dry)						
Carbon	5.01	22.52	0.66	0.66	0.35	0.99
Hydrogen	1.15	0.02	0.09	0.09	0.89	0.02
Nitrogen	<0.01	0.27	<0.01	<0.01	<0.01	0.01
Sulfur (total)	12.15	0.42	22.48	0.26	19.92	0.39
Sulfate Sulfur	1.92	----	1.89	----	7.88	----
Sulfite Sulfur	10.22	----	20.59	----	12.04	-----
Ash (750 ºC)	91.75	77.01	96.16	99.02	98.18	98.49
Major Element, wt% (dry)						
SiO_2	17.55	42.53	1.45	47.63	1.80	44.93
Al_2O_3	8.06	18.02	0.38	23.91	0.42	23.29
TiO_2	0.38	0.76	0.02	1.17	0.01	1.17
Fe_2O_3	3.56	11.75	0.16	21.16	0.18	22.57
CaO	28.81	2.06	42.11	2.45	42.59	2.56
MgO	1.33	0.72	1.43	0.92	1.37	0.80
Na_2O	0.28	0.55	0.07	0.31	0.10	0.41
K_2O	0.73	1.62	0.01	2.07	0.09	1.86
P_2O_5	0.13	0.24	<0.01	0.40	0.00	0.35
SO_3	34.09	0.61	56.21	0.64	49.81	0.98
LOI	----	22.93	----	0.98	----	1.51
Specific Gravity	2.201	2.180	-----	2.544	2.289	2.456
Particle Size Distribution, µm						
Mean diameter	11.7	----	32.6	----	----	----
Diameter below with 90% sample lie	19.9	----	58.5	----	----	----
Diameter below with 50% sample lie	10.5	----	28.6	----	----	----
Diameter below with 10% sample lie	4.9	----	10.7	----	----	----

(a) Solids concentration of 54.0%
(b) Solids concentration of 44.9%
(c) Solids concentration of 41.4%

Table 1-C-1. Analyses of FBC Ash (From Low and High Sulfur Coals)

	New Mexico Power TNP One Station (FBC-TS)	AES Guayama Station (FBC-PR)	JEA Northside Station (FBC-FS)	Tractebel Power Red Hills Station (FBC-MS)
Moisture, wt% (as rec.)	0.12	0.13	0.12	0.14
Ultimate Analysis, wt%(dry)				
Carbon	0.60	4.16	8.26	0.26
Hydrogen	0.03	0.18	0.25	<0.01
Nitrogen	<0.01	0.08	0.12	<0.01
Sulfur (total)	3.01	4.35	8.66	2.52
Sulfate sulfur	3.01	4.35	8.66	2.52
Ash (750 °C)	98.08	95.16	84.95	99.54
Major Element, wt% (dry)				
SiO_2	48.50	38.90	6.26	51.05
Al_2O_3	16.79	13.31	3.31	16.02
TiO_2	1.00	0.50	0.15	0.89
Fe_2O_3	4.47	5.91	2.60	3.92
CaO	23.00	17.61	48.77	18.44
MgO	2.62	0.64	0.62	2.48
Na_2O	0.51	2.97	0.36	0.42
K_2O	0.83	1.28	0.13	1.04
P_2O_5	0.14	0.09	0.06	0.08
SO_3	7.53	10.87	21.64	6.03
Components, wt% dry				
CaO (a)	2.5	3.3	16.5	(c)
$CaSO_4$ (b)	12.8	18.5	36.8	10.7

(a) Based on thermogravimetric analysis (TGA) or lime index measurements
(b) Based on the total sulfur content in ash
(c) None detectable

Table 1-C-2. Analyses of FBC Ash (From Waste Coal)

	PG&E Northampton Station (FBC-PS)
Moisture, wt% (as rec.)	0.08
Ultimate Analysis, wt% (dry)	
Carbon	6.40
Hydrogen	0.06
Nitrogen	0.05
Sulfur	2.42
Sulfate sulfur	2.42
Ash (750°F)	89.94
Major Element (a), wt% (dry)	
SiO_2	40.23
Al_2O_3	17.94
TiO_2	0.80
Fe_2O_3	5.65
CaO	14.81
MgO	1.76
Na_2O	0.52
K_2O	2.04
P_2O_5	0.16
SO_3	6.06
Components, wt% (dry)	
CaO (a)	2.5
$CaSO_4$ (b)	10.3

(a) Based on thermogravimetric analysis (TGA)
(b) Based on total sulfur content in ash

Table 1-D. Analyses of Pulverized Coal Fly Ash

	Class C Fly Ash from GPCO Scherer Station (FY-GS)	Class F Fly Ash from JEA Seminole Station (FY-FS)	Class F Fly Ash from First Energy Sammis Station (FY-OS)
Moisture, wt% (as rec.)	0.01	0.22	0.25
Ultimate Analysis, wt%(dry)			
Carbon	0.25	5.41	14.79
Hydrogen	<0.01	0.08	0.05
Nitrogen	<0.01	0.04	0.15
Sulfur (total)	0.45	0.45	0.13
Ash (750 □C)	99.70	93.82	84.37
Major Element, wt% (dry)			
SiO_2	37.56	44.06	47.34
Al_2O_3	19.60	18.83	24.50
TiO_2	1.45	0.98	1.26
Fe_2O_3	7.13	20.67	4.42
CaO	24.30	3.77	1.08
MgO	5.39	0.92	0.75
Na_2O	1.85	0.72	0.24
K_2O	0.64	1.88	2.02
P_2O_5	1.49	0.10	0.18
SO_3	1.13	1.13	0.33
LOI	0.30	6.18	15.63
Specific Gravity	2.608	2.388	1.971
Particle Size Distribution, μm			
Mean diameter	25.8	----	----
Diameter below with 90% sample lie	78.3	----	----
Diameter below with 50% sample lie	10.1	----	----
Diameter below with 10% sample lie	2.7	----	----

Table 1-E. Analyses of Spray Dryer Ash

	Birchwood Power Partners Station (SDA-VS)	Sunflower Power Holcomb Station (SDA-KS)
Moisture, wt% (as rec.)	1.22	1.71
Ultimate Analysis, wt%(dry)		
Carbon	5.57	0.17
Hydrogen	0.99	0.01
Nitrogen	0.05	0.08
Sulfur (total)	3.17	4.79
Sulfite sulfur	3.17	4.79
Ash (750 □C)	84.16	97.35
Major Element, wt% (dry)		
SiO_2	24.05	30.22
Al_2O_3	11.52	15.89
TiO_2	0.57	1.19
Fe_2O_3	2.21	3.79
CaO	34.13	25.66
MgO	0.89	3.90
Na_2O	0.13	1.82
K_2O	1.10	0.43
P_2O_5	0.03	1.01
SO_3	7.92	11.98
Specific Gravity	2.088	2.560
Particle Size Distribution, µm		
Mean diameter	13.5	----
Diameter below with 90% sample lie	32.5	----
Diameter below with 50% sample lie	8.9	----
Diameter below with 10% sample lie	2.3	
Components, wt%		
$Ca(OH)_2$ (a)	25.0	8.5
$CaSO_3$ (b)	11.89	17.96

Based on thermogravimetric analysis (TGA) or lime index measurement
Based on total sulfur content in ash

Preparation and Characterization of Manufactured Aggregates

The objectives of this task are to prepare manufactured aggregate and to determine the aggregate properties as the baseline for the durability study. All manufactured aggregates planned for the project were prepared and characterized. See the Experimental section for preparation details.

Test conditions and properties of pelletized and extruded products made from various CCBs as feed materials are listed below in Tables 2A-1, 2A-2, 2B-1, 2B-2, 3B-3, 2C-1, 2C-2, 2C-3, 2C-4, 2D-1, 2E-1, 2E-2 in accordance with CCBs collected from individual power stations. CCBs include limestone wet FGD, lime wet FGD, FBC ash, fly ash and spray dryer ash as discussed below.

Limestone Wet FGD

Fixated with Class C Fly Ash As shown in Table 2-A-1, four pelletization tests (Test Nos. FGD-LS-TS-1 to FGD-LS-4) were conducted to evaluate the effects of mix formulation and Class C fly ash addition on properties of aggregates made with fixated limestone wet FGD materials from Reliant Energy Limestone Station in Texas. Mixer feed, operating conditions and properties of aggregates are listed in the table for comparison. In Test Nos. FGD-LS-TS-1 and FGD-LS-TS-2, aggregate products were made from FGD filter cake, lignite fly ash, hydrated lime and water with slightly different mix ratios. The aggregates produced had crush strengths of 79±11 lb and 90±10 lb, unit weights of 69.9 lb/ft^3 and 72.9 l/ft^3 (as-is) and 63.4 lb/ft^3 and 68.1 lb/ft^3 (dry), respectively. In Test No. FGD-LS-TS-3, a subbituminous coal fly ash (Class C) was used to replace 50% of the lignite fly ash in the mix feed. The aggregates produced had a crush strength of 226±78 lb and unit weights of 74.0 lb/ft^3 (as-is) and 68.3 lb/ft^3 (dry). In Test No. FGD-LS-TS-4, 100% Class C fly ash was used as the fly ash component in the mix feed. The aggregates produced had a crush strength of 246±45 lb and unit weights of 75.2 lb/ft^3 (as-is) and 69.6 lb/ft^3 (dry). In all tests, unit weights were determined with crushed aggregates meeting ASTM No. 8 and 9 size gradations (combined fine and coarse aggregates).

Test results show that the crush strength of aggregate increased substantially with addition of Class C fly ash in mix feed. Aggregates with high crush strength (over 200 lb) can be made with Class C fly ash in fixated FGD material. However, dry unit weights of aggregates produced did not meet the ASTM C331 specification (i.e., 65 lb/ft^3, max. for combined aggregate) for use as lightweight aggregate in concrete masonry units (CMU). The strong aggregate may be used in road construction.

The aggregate made with 100% Class C fly ash in Test No. FGD-LS-TS-4 was selected for use in the durability study in the next task.

<u>Fixated with Class F Fly Ash.</u> As shown in Table 2-A-2, three pelletization tests (Test Nos. FGD LS-FS-1 to FGD-LS-FS-3) and one extrusion test (Test No. FGD-LS-FS-4) were conducted to evaluated the effects of mix formulation and Class F fly ash addition on properties of aggregates made with fixated limestone wet FGD materials from Lakeland McIntosh Station in Florida. Mixer feed, operating conditions and properties of aggregates are listed in the table for comparison. In Test Nos. FGD-LS-FS-1 and FGD-LS-FS-2, aggregate products were made from FGD filter cake, Class F fly ash, hydrated lime and water with different mix ratios. The aggregates produced had crush strengths of 164±40 lb and 143±36 lb, unit weights of 61.2 lb/ft^3 and 65.0 lb/ft^3 (as-is) and 54.0 lb/ft^3 and 56.8 lb/ft^3 (dry), respectively. The aggregate produced from Test No. FGD-LS-FS-2 had a soundness index of 21.6%. In Test No. FGD-LS-FS-3, bottom ash was added to the mix feed. The aggregate produced had a crush strength of 121±24 lb and unit weight of 64.3 lb/ft^3 (as-is) and 55.7 lb/ft^3 (dry). In Test No.FGD-LS-FS-4, the aggregate produced from extrusion had a crush strength of 464±43 lb and unit weights of 64.6 lb/ft^3 (as-is) and 55.6 lb/ft^3 (dry). The crush strength was higher than those with aggregates made from disk pelletization, because products with different dimensions were used for the measurements. For the extrusion product, the aggregate crush strength was determined with cylindrical extruded products with lengths of 1.5" to 1.7" and diameter of 1". For the disk pelletization product, the aggregate crush strength was determined with spherical palletized products with ½" x 3/8" diameters. In all tests, unit

weights were determined with crushed aggregates meeting ASTM No. 8 and 9 size gradation (combined fine and coarse aggregates).

Test results show that aggregates produced had adequate crush strengths for use in CMU production. Based on the previous block production demonstration work at CONSOL Energy and Universal Aggregates, aggregate with crush strength over 100 lb (prepared from disk pelletization) and over 400 lb (prepared from extrusion) can produce CMU meeting ASTM C90 compressive strength specification. Dry unit weights of aggregates met the ASTM C331 specification (65 lb/ft^3, max. for combined aggregate) for use as lightweight weight in CMU. In comparison, the aggregate produced in Test No. FGD-LS-FS-2 had a soundness index of 21.6%, which does not meet AASHTO Class A aggregate specifications (12%, max.) for used in road construction.

In a separate project, internally funded by Universal Aggregates, lightweight aggregate was produced at the pilot plant scale and the product was used in block production demonstration. The mix formulation and operation conditions used at the pilot plant were similar to those used in Test No.FGD-LS-FS-4. The aggregate produced from Test No. FGD-LS-FS-2 was used in the aggregate durability study. The aggregate produced from the pilot plant was used for CMU production and for aggregate products durability study.

Lime Wet FGD

<u>Fixated with High LOI Fly Ash.</u> As shown in Table 2-B-1, three pelletization tests (Test Nos. FGD-LM-PS-1 to FGD-LM-PS-3) were conducted to evaluate the effects of mix formation and high LOI fly ash (22.93% in Table 1-B) on properties of aggregates made with fixated lime wet FGD from Reliant Energy Elrama Station in Pennsylvania. Mixer feed, operating conditions and properties of aggregates are listed in the table for comparison. In Test Nos. FGD-LM-PS-1 and FGD-LM-PS-2, products were made from FGD filter cake, high LOI fly ash, quick lime and water with different mix ratios. The aggregates produced had a crush strengths of 37±12 lb and 58±19 lb, LA abrasion index of 59.9% and 42,6%, unit weights of 55.3 lb/ft^3 and 58.3 lb/ft^3 (as-is) and 51.4 lb/ft^3 and 53.1 lb/ft^3 (dry), respectively. In Test No. FGD-LM-FS-3, hydrated lime was used to replace quick lime in mix feed. The aggregate produced had a crush strength of 97±31 lb, LA abrasion index of 34,6%, unit weights of 63.9 lb/ft^3 (as-is) and 57.5 lb/ft^3 (dry) and soundness index of 81.0%. In all tests, unit weights were determined with crushed aggregates meeting ASTM No. 8 and 9 size gradation (fine and combined aggregates).

Test results show that all aggregates produced from these tests had a crush strength less than 100 lb. The aggregate crush strengths did not meet the strength criteria (100 lb, min.) for use in CMU production, even though aggregate unit weights meet the ASTM C331 specification for use as lightweight aggregate in CMU. The aggregates produced in Test Nos. FGD-LM-PS-1 and FGD-LM-PS-2 had LA abrasion indices of 59.9% and 42.6%. The aggregate produced in Test No. FGD-LM-PS-3 had soundness index of 81.1%. These index values did not meet AASHTO Class A specifications of LA abrasion index (40%, max.) and soundness index (12%, max.) for use in road construction.

The aggregate produced in Test No. FGD-LM-PS-3 was selected for use as reference in the aggregate durability study in Task 4.

Fixated with Low LOI Fly Ash. As shown in Table 2-B-2, four pelletization tests (Test Nos. FGD-LM-OS-1-1 to FGD-LM-OS-1-4) were conducted to evaluate the effects of mix formulation and low LOI fly (0.98% in Table 1-B) ash on properties of aggregates made with fixated lime wet FGD materials from AEP Gavin Station in Ohio. Mixer feed, operating conditions and properties of aggregates are listed in the table for comparison. In Test No. FGD-LS-OS-1-1, aggregate was made from FGD filter cake, low LOI fly ash, quick lime and water. The aggregate produced had a crush strength of 106±26 lb, LA abrasion index of 51%, unit weights of 73.7 lb/ft^3 (as-is) and 66.3 lb/ft^3 (dry) and soundness index 0f 49%. In Test No. FGD-LS-OS-1-2, hydrated lime was used to replace quick lime in mix feed. The crush strength increased to 106±26 lb. The LA abrasion and soundness indices decreased to 45% and 46%, respectively. The aggregate had unit weights of 72.3 lb/ft^3 (as-is) and 65.1 lb/ft^3 (dry). In Test No. FGD-LS-OS-1-3, hydrated lime content in mix feed increased to 12.8%. The aggregate produced had a crush strength of 123±49 lb, LA abrasion index of 42%, unit weights of 74.3 lb/ft^3 (as-is) and 66.8 lb/ft^3 (dry) and soundness index of 79%. In Test No. FGD-LS-OS-1-4, the mix feed is the same as those in Test No. FGD-LS-OS-1-3 except that 13.2% of cement was added to replace fly ash. The crush strength increased substantially to 232±88 lb and the LA abrasion and soundness indices decreased substantially to 30% and 5% respectively,. The aggregate had unit weights of 75.8 lb/ft^3 (as-is) and 68.1 lb/ft^3 (dry). In all tests, the unit weights were determined with crushed coarse aggregates with 50% or more above ½".

Test results show that aggregate with high crush strength (over 200 lb) can be made with cement addition, but not with increased hydrated lime content in the mix feed. In all tests, dry unit weights of aggregates produced did not meet the ASTM C331 specification (i.e., 55 lb/ft^3, max. for coarse aggregate) for use as lightweight aggregate in CMU production. However, the aggregates produced from Test No. FGD-LM-OS-1 to FGD-LM-OS-4 met AASHTO LA abrasion (40%, max.) and soundness (12% max.) indices specifications for use as coarse aggregate in road construction.

The aggregate produced from Test No. FGD-LM-OS-4 was selected for use in the aggregate durability study in Task 4.

Fixated With Low and High LOI Fly Ash. As shown in Table 2-B-3, three pelletization tests (Test Nos. FGD-LM-OS-2-1 to FGD-LM-OS-2-3) were conducted to evaluate the effects of mix formulation and low and high LOI fly ash addition on properties of aggregates made from fixated lime wet FGD materials. FGD filter cake and low LOI fly ash (1.51% LOI in Table 1-B) with high specific gravity (2.456 in Table 1-B) were collected from AEP Conesville Station in Ohio. High LOI fly ash (15.63%, Table 1-D) with low specific gravity (1.971, Table 1-D) was collected from First Energy Sammis station in Ohio. Mixer feed, operating conditions and properties of aggregates are listed in the table for comparison. In Test No. FGD-LM-OS-2-1, aggregate products were made from FGD filter cake, low LOI Conesville fly ash hydrated lime and water. The aggregate produced had a crush strength of 130±26 lb, unit weights of 65.3 lb/ft^3 (as-is) and 56.8 lb/ft^3 (dry). In Test Nos. FGD-LM-OS-2-2 and FGD-LM-OS-2-3, 25% and 50% of low LOI Conesville fly ash were replaced with high LOI Sammis fly ash in mix feed. The aggregates produced had crush strengths of 184±28 and 186±36 lb, respectively. Unit weights decreased to 63.5 lb/ft^3 (as-is) and 54.4 lb/ft^3 (dry) in Test No.FGD-LM-OS-2-2 and to 61.9 lb/ft^3 (as-is) and 52.0 lb/ft^3 (dry) in Test No. FGD-LM-OS-2-3. In all tests, unit weights were determined with crushed aggregates meeting ASTM No. 8 and 9 size gradation (combined fine and coarse aggregates).

Test results show that aggregates produced had adequate crush strength and unit weight for use as lightweight aggregate in CMU production. The unit weight decreased with increasing amount of high LOI and low specific gravity Sammis fly ash addition in mix feed. At 50/50 Conesville and Sammis Station fly ash with combined LOI of 8.57% (Test No. FGD-LM-OS-2-3), aggregate produced had a crush strength of 186±36 lb. The crush strength was higher than that (130±26 lb) of the aggregate produced with 100% Conesville Station fly ash with LOI of 1.51%. In comparison, the aggregate produced from fixated lime wet FGD materials with high LOI fly ash (22.93% of LOI), as shown in Table 2-B-1, had low crush strength of 97±31 lb. This indicates that aggregate strength may improve with addition of fly ash with moderate increase in LOI, but not with high LOI.

In a separate project, funded by OCDO,[1, 2] lightweight aggregate was produced from the pilot plant operation and was used in block production demonstration tests. The mix formulation and operating conditions used in the pilot plant demonstration were similar to those used in Test No. FGD-LM-OS-2-3. The aggregate produced from the pilot plant was selected for use in the aggregate products durability study in Task 5.

FBC Ash

<u>FBC Ash from Low Sulfur Texas Lignite</u>. As shown in Table 2-C-1, three pelletization tests (Test Nos. FBC-TS-1 to FBC-TS-3) were conducted to evaluate the effect of mix formulation and operating conditions on properties of aggregates made with FBC ash from New Mexico Power TNP One Station. Mixer feed, operating conditions and properties of aggregates are listed in the table for comparison. The FBC ash was generated from a low-sulfur Texas lignite. In Test Nos. FBC-TS-1 to FBC-TS-3,.aggregate products were made from FBC ash and water with mixing time increased from 20 minutes to 25 minutes and to 30 minutes. The aggregates produced had crush strengths of 347±157 lb, 279±102 lb and 329 ±78 lb, and unit weights of 70.8 lb/ft^3, 66.5 lb/ft^3 and 65.9 lb/ft^3 (as-is) and 63.2 lb/ft^3, 58.7 lb/ft^3 and 58.2 lb/ft^3(dry), respectively. In all tests, unit weights were determined with crushed aggregates meeting ASTM No. 8 and 9 size gradation (combined fine and coarse aggregates).

Test results show that the aggregates produced had high crush strengths (over 200 lb) and adequate unit weights meeting ASTM C 331 lightweight aggregate specifications for use in CMU production. The high strength aggregates may be used in road construction.

The aggregate made from Test No. FBC-TS-3 was selected for use in the aggregate durability study in Test 4.

FBC Ash from Low-Sulfur Coal. As shown in Table 2-C-2, two pelletization tests (Test Nos. FBC-PR-1 and FBC-PR-2) and one extrusion test (Test No. FBC-PR-3) were conducted to evaluate mix formulation and operating conditions on properties of aggregates made with FBC ash from AES Guayama Station in Puerto Rico. Mixer feed, operating conditions and properties of aggregates are listed in the table for comparison.. The FBC ash was generated from a low-sulfur Columbia coal. In Test Nos. FBC-PR-1 and FBC-PR-2, aggregates products were made from FBC ash and water with mixing time of 20and 30 minutes. The aggregates produced had crush strengths of 203±55 lb and 245±65 lb and unit weights of 69.5 lb/ft^3 and 65.0 lb/ft^3 (as-is) and 60.3 lb/ft^3 and 55.5 lb/ft^3 (dry). In Test No. FBC-PR-3, the aggregate produced from extrusion with 26 minute mixing time had a crush strength of 708±120 lb and unit weights of 62.0 lb/ft^3 (as-is) and 54.2 lb/ft^3 (dry). In extrusion, the crush strength was determined with cylindrical extruded products with lengths of 1.5" to 1.7" and diameter of 1". In disk pelletization, the crush strength was determined with spherical palletized products with ½" x 3/8" diameters. In all tests, unit weights were determined with crushed aggregates meeting No. 8 and 9 size gradation (combined fine and coarse aggregates).

The aggregates produced had strong crush strengths meeting the requirements of 100 lb (min.) for pelletized products and 400 lb (min.) for extruded products, and had adequate dry unit weights meeting ASTM C331 specification (65 lb/ft^3, max.) for use as lightweight aggregate in CMU production.

The aggregates produced from Test No. FBC-PR-3 was selected for use in the aggregate durability study in Task 4.

FBC Ash from Low-Sulfur Mississippi Lignite. As shown in Table 2-C-3, two pelletization tests (Test Nos. FBC-MS-1 and FBC-MS-2) and one extrusion test (Test No. FBC-MS-3) were conducted to evaluate the effects of mix formulation on properties of aggregates made with FBC ash from Tractebel Power Red Hills Station in Mississippi.   Mixer feed, operating conditions and properties of aggregates are listed in the table for comparison. The FBC ash was generated from a low-sulfur Mississippi lignite. In Test Nos. FBC-MS-1 and FBC-MS-2, aggregate products were made from FBC ash and water with mixing time of 20 and 30 minutes. The aggregates produced had crush strengths of 179±35 lb and.211±89 lb.   The aggregate produced in Test No. FBC-MS-2 had unit weights of 63.8 lb/ft^3 (as-is) and 53.7 lb/ft^3 (dry). In Test No. FBC-MS-3, the aggregates produced from extrusion with 20 minute mixing time had crush strengths of 467±42 lb and unit weights of 62.4 lb/ft^3 (as-is) and 55.2 lb/ft^3 (dry). In all tests, unit weights were determined with crushed aggregates meeting No. 8 and 9 size gradation (combined fine and coarse aggregates).

As in the Guayama Station FBC ash aggregate, the aggregates produced from Red Hill Station FBC ash had adequate crush strength and unit weights for use as lightweight aggregates in CMU production.

The aggregates produced from Test No. FBC-MS-3 was selected for use in the aggregate durability study in Task 4.

FBC Ash from High Sulfur Coal. As shown in Table 2-C-4, three pelletization tests (Test Nos. FBC-FS-1 to FBC-FS-3) and one extrusion test (Test No. FBC-FS-4) were conducted to evaluate the effects of mix formulation and fly ash addition on properties of aggregates made with FBC ash from JEA Northside Station in Florida and with fly ash (Class F) from Lakeland McIntosh Station in Florida. Mixer feed, operating conditions and properties of aggregates are listed in the table for comparison. The FBC ash was generated from a 30/70 blend of high-sulfur coal (3% S) and petcoke (6.4% S). In Test No. FBC-FS-1, aggregate was made from FBC ash with mixing time of 20 minutes. The aggregate produced had a crush strength of 240±80 lb. In Test Nos. FBC-FS-2 and FBC-FS-3, 10% and 30% of Lakeland fly ash were added in the mix feed. The aggregates produced had crush strengths of 221±72 lb and 348±112 lb, respectively. Unit weights and size gradation were not determined in these tests. In Test No. FBC-FS-4, the aggregate produced from extrusion with 20 minute mixing time had a crush strength of 420±123 lb and unit weights of 61.4 lb/ft^3 (as-is) and 55.4 lb/ft^3 (dry).

As in aggregates produced from low-sulfur coal FBC ash, the aggregate produced from high-sulfur coal FBC ash had adequate crush strength and unit weight for use as lightweight aggregate in CMU production.

The aggregates produced from Test Nos. FBC-FS-1 to FBC-FS-3 with and without fly ash addition in mix feed were selected for use in the aggregate durability study in Task 4.

FBC Ash from Waste Coal. As shown in Table 2-C-5, two pelletization tests were conducted to evaluate the mix formulation and operating conditions on properties of aggregate made with FBC ash from PG&E Northampton Station in Pennsylvania. Mixer feed, operating conditions and properties of aggregates are listed in the table for comparison. The FBC ash was generated from waste coal (or gob). In Test Nos. FBC-PS-1 and FBC-PS-2, aggregates produced had crush strengths of 301±52 lb and 298±72 lb and unit weights of 65.4 lb/ft^3 and 68.2 lb^3 (as-is) and 54,0 lb/ft^3 and 60.0 lb/ft^3 (dry), respectively. Unit weights were determined with crush aggregates meeting ASTM No. 8 and 9 size gradation (combined fine and coarse aggregates).

The aggregates produced had adequate crush strengths and unit weights for use as lightweight aggregate in CMU production. Since there is no significant differences in crush strength and unit weight with aggregates produced from other low-sulfur coal FBC ash, these aggregates were not used for the durability study.

Pulverized Coal Fly Ash

<u>Class F and Class C Fly Ash.</u> As shown in Table 2-D-2, three pelletization tests (Test Nos. FY-FS-1 to FY-FS-3) were conducted to evaluate the effects of mix formulation and Class F and Class C fly ash addition on properties of aggregates made from pulverized coal fly ash only. The Class F fly ash was collected from JEA Seminole Station in Florida,. The Class C fly ash was collected from GPCO Scherer Station in Georgia. Mixer feed, operating conditions and properties of aggregates are listed in the table for comparison. In Test Nos. FY-FS-1 and FY-FS-2, aggregate products were made from Class F fly ash, hydrated lime and water with slightly different mix ratios. The aggregates produced had crush strengths of 103±lb and 113±28 lb and unit weights of 72.6 lb/ft and 72.6 lb/ft^3 (as-is) and 71.4 lb/ft^3 and 66.5 lb/ft^3 (dry). In Test No. FY-FS-3, 20% of Class F fly ash was replaced with Class C fly ash in mix feed. The aggregate produced had higher crush strength of 204±32 lb and unit weights of 77.5 lb/ft^3 (as-is) and 72.8 lb/ft^3 (dry). In all tests unit weights were determined with crushed aggregates meeting ASTM No. 8 and 9 size gradation.

Test results show that crush strength and unit weight of aggregate increased substantially with addition of Class C fly ash. Dry unit weights of aggregates did not meet the ASTM C331 lightweight aggregate specification for use in CMU production, even without Class C fly ash addition. These aggregates were not selected for the durability study, because they did not meet the ASTM C331 specifications.

Spray Dryer Ash

<u>Spray Dryer Ash with Class F Fly Ash.</u> As shown in Table 2-E-1, three pelletization tests (Test Nos. SDA-VS-1 to SDA-VS-3) and one extrusion run (Test No. SDA-VS-4) were conducted to evaluate the effects of mix formulation and operating conditions on properties of aggregates made with spray dryer ash (SDA) from Birchwood Power Station in Virginia. The SDA contains Class F fly ash, which was generated from a low-sulfur bituminous coal. In Test No. SDA-VS-1, aggregate was made from SDA, hydrated lime and water. The aggregate produced had a crush strength of 181±61 lb and unit weights of 58.6 lb/ft^3 (as-is) and 51.6 lb/ft^3 (dry). In Test Nos. SDA-VS-2 and SDA-VS-2, 3% and 6% of cement (based on dry basis) were added in the mix feeds. The aggregates produced had crush strengths of 181±39 lb and 150±46 lb, unit weights of 59.2 lb/ft^3 and 59.2 lb/ft^3 (as-is) and 49.0 lb/ft^3 and 51.0 lb/ft^3 (dry), respectively. In Test No. SDA-VS-4, the aggregate produced from extrusion had a crush strength of 484±106 lb and unit weights of 54.2 lb/ft^3 (as-is) and 47.8 lb/ft^3 (dry). In extrusion, the crush strength was determined with cylindrical extruded products with lengths of 1.5” to 1.7” and diameter of 1”. In disk pelletization, the crush strength was determined with spherical pelletized products with ½” x 3/8” diameters. In all tests, unit weights were determined with crushed aggregates meeting ASTM No. 8 and 9 size gradation (combined fine and coarse aggregates).

Test results show that aggregates produced from the above tests had adequate crush strength and unit weight for use as lightweight aggregate in CMU production. Addition of cement in mix feed did not increase the aggregate crush strength.

The aggregates produced from Test Nos. SDA-VS-1 and SDA-VS-3 were used to study the effects of cement addition in the durability study.

In a separate project, internally funded by Universal Aggregates, lightweight aggregate was produced in the pilot plant and used in block production demonstration. The mix formulation and operation conditions used in the pilot plant were similar to those used in Test No. SDA-VS-4. The aggregate produced from the pilot plant was selected for use in the aggregate products durability study.

<u>Spray Dryer Ash with Class C Fly Ash.</u> As shown in Table 2-E-2, three pelletization tests (Test Nos. SDA-KS-1 to SDA-KS-3) were conducted to evaluate the effect of mix formulation and operating conditions on properties of aggregates made with SDA from Sunflower Power Station in Kansas. Mixer feed, operating conditions and properties of aggregates are listed in the table for comparison. The SDA contained Class C fly ash, which was generated from a low-sulfur subbituminous coal. In Test No. SDA-KS-1, aggregate was made from SDA, hydrated lime and water with 4 minute mixing time. The aggregate produced had a crush strength of 177±69 lb and unit weights of 73.4 lb/ft^3 (as-is) and 67.4 lb/ft^3 (dry). In Test Nos. SDA-KS-2 and SDA-KS-3, the mixing time was increased to 20 minutes. The aggregates produced had crush strengths of 221±67 lb and 204±56 lb and unit weights of 74.1 lb/ft^3 and 74.0 lb/ft^3 (as-is) and 67.2 lb/ft^3 and 67.1 lb/ft^3 (dry), respectively. In all tests unit weights were determined with crushed aggregates meeting ASTM No. 8 and 9 size gradation (combined fine and coarse aggregates).

Test results show that aggregate with high crush strength (over 200 lb) can be produced from SDA with Class C fly ash and 20 minute mixing time. However, dry unit weights produced did not meet the ASTM C331 specification (i.e., 65 lb/ft^3, max. for combined aggregate) for use as lightweight aggregate in CMU production. The strong aggregate may be used in road construction.

The aggregates made from Test Nos. SDA-KS-1 and SDA-KS-3 with different mixing time were selected for use in the durability study in Task 4.

Table 2-A-1. Test Conditions and Properties of Pelletized Products Made with Fixated Wet Limestone Materials from Reliant Energy Limestone Station in Texas (Limestone Wet FGD with Class C Fly Ash)

Test Nos. FGD-LS-TS-	1	2	3	4
Mixer Feed, wt%				
FGD Filter Cake, as-is	37.1	37.8	37.4	38.0
Lignite Fly Ash	54.3	55.1	27.3	0
Subbituminous Fly Ash (Class	0	0	27.3	58.2
C)	5.2	6.1	6.0	5.8
Hydrated Lime	3.4	1.0	2.0	3.0
Water				
	4.0	4.0	4.0	8.0
Mixing Time, min				
Pelletizer Feed	ca. 13.4	ca. 13.4	ca. 13.4	ca. 13.4
Feed Rate, lb/min	3.4	0	0	0
Water Added, wt%				
	ca. 25	ca. 25	ca. 25	ca. 20
Pelletization Time, min				
	160-170	160-170	160-170	160-170
Curing Temperature, °F				
Product Properties	79±11	90±10	226±78	246±45
Crush Strength, lb				
Unit Weight, lb/ft^3	69.9	72.9	74.0	75.2
as-is	63.4	68.1	68.3	69.6
dry	Nos. 8/9	Nos. 8/9	Nos. 8/9	Nos. 8/9
Particle Size, wt% pass	(Combined)	(Combined)	(Combined)	(Combined)

Table 2-A-2. Test Conditions and Properties of Pelletized Products Made with Fixated Limestone FGD Materials from Lakeland McIntosh Station in Florida (Limestone Wet FGD with Class F Fly Ash)

Test Nos. FGD-LS-FS-	1	2	3	4 (a)
Mixer Feed, wt%				
FGD Filter Cake, as is	26.4	47.0	40.0	39.7
Fly Ash (Class F)	40.7	47.0	44.0	43.2
Bottom Ash	----	----	10.0	8.5
Hydrated Lime	4.4	6.0	6.0	6.0
Water	28.6	0	0	2.6
Mixing Time, min	4.0	4.0	4.0	4.0
Pelletizer Feed				
Feed Rate, lb/min	ca. 13.4	ca. 13.4	ca. 13.4	ca. 13.4
Water Added, lb	0	0	0	0
Pelletization Time, min	ca. 25	ca. 20	ca. 20	ca. 20
Curing Temperature, °F	160-170	160-170	160-170	160-170
Product Properties				
Crush Strength, lb	164±40	143±36	121±24	464±43 (b)
Unit Weight, lb/ft^3				
As-is	61.2	65.0	64.3	64.6
Dry	54.0	56.8	55.7	55.6
Soundness Index, %	----	21.6	-----	----
Particle Size, wt% pass	Nos. 8/9 (Combined)	Nos. 8/9 (Combined)	Nos. 8/9 (Combined)	Nos. 8/9 (Combined)

(a) Produced by extrusion run
(b) Average of ten measurements with extruded products with lengths of 1.5” to 1.7” and diameter of 1”

Table 2-B-1. Test Conditions and Properties of Pelletized Products Made with Fixated Wet Lime FGD Materials from Reliant Energy's Elrama Station in Pennsylvania (Lime Wet FGD with High LOI Fly Ash)

Test Nos. FGD-LM-PS-	1	2	3
Mixer Feed, wt%			
FGD Filter Cake	42.7	60.3	60.1
Fly Ash	42.3	33.2	33.1
Lime	4.0	4.0	----
Hydrated Lime	----	----	5.2
Water	11.0	2.5	1.6
Mixing Time, min	2.0	2.0	4.0
Pelletizer Feed			
Feed Rate, lb/min	ca. 13.4	ca. 13.4	ca. 13.4
Water Added, wt%	2.4	0.48	0
Pelletization Time, min	ca. 25	ca. 25	ca. 25
Curing Temperature, °F	160-170	160-170	160-170
Product Properties			
Crush Strength, lb	37±12	58±19	97±31
LA Abrasion Index, %	59.9	42.6	34.6
Unit Weight, lb/ft^3			
as-is	55.3	58.3	63.9
dry	51.4	53.1	57.5
Soundness Index, %	---	---	81.0
Particle Size, wt% pass	Nos. 8/9 (Combined)	Nos. 8/9 (Combined)	Nos. 8/9 (Combined)

Table 2-B-2. Test Conditions and Properties of Pelletized Products Made with Fixated FGD Materials from AEP Gavin Station in Ohio (Lime Wet FGD with Low LOI Fly Ash)

Test Nos. FGD-LM-OS-1-	1	2	3	4
Mixer Feed, wt%				
FGD Sludge, as is	43.9	43.0	41.6	43.0
Fly Ash	52.0	51.4	45.6	38.2
Lime	4.1	---	----	0
Hydrated Lime	----	5.6	12.8	5.6
Cement	----	----	----	13.2
Water	0	0	0	0
Mixing Time, min	4.0	4.0	4.0	4.0
Pelletizer Feed				
Feed Rate, lb/min	ca. 13.4	ca. 13.4	ca. 13.4	ca. 13.4
Water Added, wt%	0	0	0	0
Pelletization Time, min	ca. 25	ca. 25	ca. 25	ca. 25
Curing Temperature, $^{\circ}$F	160-170	160-170	160-170	160-170
Product Properties				
Crush Strength, lb	78±29	106±26	123 ± 49	232±88
LA Abrasion Index, %	51	45	42	30
Unit Weight, lb/ft^3				
as-is	73.7	72.3	74.3	75.8
dry	66.3	65.1	66.8	68.1
Soundness Index, %	49	46	79	5
Particle Size, wt% pass				
1"	98.0	93.5	93.4	96.5
3/4"	86.1	78.3	75.8	85.1
1/2"	49.9	46.3	43.6	50.3
3/8"	18.2	28.8	26.5	25.1
4 mesh	9.4	12.8	9.8	8.7
8 mesh	7.1	2.7	5.9	5.3

Table 2-B-3. Test Conditions and Properties of Pelletized Products Made with Fixated Wet Lime FGD Materials from AEP Conesville Station in Ohio (Lime Wet FGD with High and Low LOI Fly Ash)

Test Nos. FGD-LM-OS-2-	**1**	**2**	**3**
Mixer Feed, wt%			
FGD Filter Cake, as is	39.5	39.3	41.1
Conesville Fly Ash (Low LOI)	54.5	40.7	26.7
Sammis Fly Ash (High LOI)	0	13.5	26.2
Hydrated Lime	6.0	6.0	6.0
Water	0	0.5	0.5
Mixing Time, min	8.0	4.0	4.0
Pelletizer Feed			
Feed Rate, lb/min	ca. 13.4	ca. 13.6	ca. 13.4
Water Added, wt%	0	0	0
Pelletization Time, min	ca. 25	ca. 25	ca. 25
Curing Temperature, °F	160-170	160-170	160-170
Product Properties			
Crush Strength, lb	130±26	184±28	186±36
Unit Weight, lb/ft^3			
as-is	65.3	63.5	61.9
dry	56.8	54.4	52.0
Particle Size, wt% pass	Nos. 8/9 (Combined)	Nos. 8/9 (Combined)	Nos. 8/9 (Combined)

Table 2-C-1. Test Conditions and Properties of Pelletized Products Made with Low Sulfur FBC Ash from New Mexico Power TNP One Station (FBC Ash from Low Sulfur Texas Lignite)

Test Nos. FBC-TS-	1	2	3
Mixer Feed, wt%			
FBC Ash	70.9	70.9	71.4
Water	29.1	29.1	28.6
Mixing Time, min	20	25	30
Pelletizer Feed			
Feed Rate, lb/min	ca. 13.4	ca. 13.4	ca. 13.4
Water Added, wt%	0	0	0
Pelletization Time, min	ca. 25	ca. 30	ca. 30
Curing Temperature, °F	160-170	160-180	160-170
Product Properties			
Crush Strength, lb	347±157	279±102	329 ± 78
Unit Weight, lb/ft^3			
As-is	70.8	66.5	65.9
Dry	63.2	58.7	58.2
Particle Size, wt% pass	No. 8/9 (Combined)	No. 8/9 (Combined)	No. 8/9 (Combined)

Table 2-C-2. Test Conditions and Properties of Pelletized Products Made with Low Sulfur FBC Ash from AES Guayama Station in Puerto Rico (FBC Ash from Low Sulfur Coal)

Test Nos. FBC-PR-	**1**	**2**	**3 (a)**
Mixer Feed, wt%			
FBC Ash	74.5	71.5	73.7
Water	25.5	28.5	26.3
Mixing Time, min	20	30	26
Pelletizer Feed			
Feed Rate, lb/min	ca. 13.4	ca. 13.4	ca. 13.4
Water Added, wt%	0		0
Pelletization Time, min	ca. 25	ca. 25	ca. 25
Curing Temperature, °F	160-170	160-170	160-170
Product Properties			
Crush Strength, lb	203±55	245±65	708±120 (b)
Unit Weight, lb/ft^3			
As-is	69.5	65.0	62.0
Dry	60.3	55.5	54.2
Particle Size, wt% pass	No. 8/9 (Combined)	No. 8/9 (Combined)	No. 8/9 (Combined)

(a) Produced by Extrusion run
(b) Average of ten measurements of extruded products with lengths of 1.5” to 1.7” and diameter of 1”

Table 2-C-3. Test Conditions and Properties of Pelletized and Extruded Products Made with Low Sulfur FBC Ash from Tractebel Power Red Hills Station in Mississippi (FBC Ash from Low Sulfur Lignite)

Test Number FBC-MS-	**1**	**2**	**3 (a)**
Mixer Feed, wt%			
FBC Ash	70.6	70.2	69.6
Water	29.6	29.8	30.4
Mixing Time, min	20	30	20
Pelletizer Feed			
Feed Rate, lb/min	ca. 13.4	ca. 13.4	ca. 13.4
Water Added, lb	0	0	0
Pelletization Time, min	20	20	20
Curing Temperature, °F	160-170	160-170	160-170
Product Properties			
Crush Strength, lb	179±35	211±89	467±42 (b)
Unit Weight, lb/ft^3			
As-is	----	63.8	62.4
Dry	----	53.7	55.2
Particle Size, wt% pass	Nos. 8/9 (Combined)	Nos. 8/9 (Combined)	Nos. 8/9 (Combined)

(a) Produced by extrusion run
(b) Average of ten measurements of extruded products with lengths of 1.5” to 1.7” and diameter of 1”

Table 2-C-4. Test Conditions and Properties of Pelletized and Extruded Products Made with High Sulfur FBC Ash from JEA Northside Station in Florida (FBC Ash from High Sulfur Coal and Coke)

Test Nos. FBC-FS	**1**	**2**	**3**	**4 (a)**
<u>Mixer Feed, wt%</u>				
FBC ash	73.9	67.5	53.2	72.7
Lakeland Fly Ash (p. c.)	0	7.5	22.8	0
Water	26.1`	25.0	24.0	27.3
<u>Mixing Time, min</u>	20	20	20	20
<u>Pelletizer Feed</u>				
Feed Rate, lb/min	ca. 13.4	ca. 13.4	ca. 13.4	ca. 13.4
Water Added, lb	0	0	0	0
<u>Pelletization Time, min</u>	ca. 25	ca. 25	ca. 25	ca. 25
<u>Curing Temperature, °F</u>	160 - 170	160-170	160-170	160–170
<u>Product Properties</u>				
Crush Strength, lb	240±80	221±72	348±112	420±123 (b)
Unit Weight, lb/ft^3				
As-is	----	----	----	61.4
Dry	-----	----	----	55.4
Particle Size, wt% pass	-----	----	----	Nos. 8/9 (Combined)

(a) Extrusion run
(b) Average of ten measurements of extruded products with lengths of 1.5” to 1.7” and diameter of 1”

Table 2-C-5. Test Conditions and Properties of Pelletized Products Made with Waste Coal FBC Ash from PG&E Northampton Station in Pennsylvania (FBC Ash from Waste Coal)

Test No. FBC-PS-	**1**	**2**
Mixer Feed, wt%		
FBC Ash	71.9	75.5
Water	28.1	25.5
Mixing Time, min	10	20
Pelletizer Feed		
Feed Rate, lb/min	ca. 13.4	ca. 13.4
Water Added, lb	0	0
Pelletization Time, min	ca. 25	ca. 20.
Curing Temperature, °F	160 - 170	160 - 170
Product Properties		
Crush Strength, lb	301±52	298±72
Unit Weight, lb/ft^3		
As-is	65.4	68.2
Dry	54.9	60.0
Particle Size, wt% pass	Nos. 8/9 (Combined)	Nos. 8/9 (Combined)

Table 2-D-1. Test Conditions and Properties of Pelletized Products Made with Class F Fly Ash from JEA Seminole Station in Florida and Class C Fly Ash from GPCO Scherer Station in Georgia (Class F and Class C Fly Ash)

Test No. FY-FS-	**1**	**2**	**3**
Mixer Feed, wt%			
Fly Ash (Class F)	76.7	75.0	77.0
Fly Ash (Class C)	----	----	15.4
Hydrated Lime	4.9	4.8	4.9
Water	18.4	20.2	18.0
Mixing Time, min	4.0	4.0	4.0
Pelletizer Feed			
Feed Rate, lb/min	ca. 13.4	ca. 13.4	ca. 13.4
Water Added, wt%	0	0	0
Pelletization Time, min	ca. 20	ca. 20	ca. 20
Curing Temperature, ºF	160-170	160-170	160-170
Product Properties			
Crush Strength, lb	103±67	113±28	204±32
Unit Weight, lb/ft^3			
As-is	75.5	72.6	77.5
Dry	71.4	66.5	72.8
Particle Size, wt% pass	Nos. 8/9 (Combined)	Nos. 8/9 (Combined)	Nos. 8/9 (Combined)

Table 2-E-1. Test Conditions and Properties of Pelletized and Extruded Products Made with SDA Containing Class F Fly Ash from Birchwood Power Station in Virginia (Spray Dryer Ash with Class F Fly Ash)

Test Nos. SDA-VS-	**1**	**2**	**3**	**4 (a)**
Mixer Feed, wt%				
Spray Dryer Ash	68.8	66.4	64.6	69.6
Hydrated Lime	4.3	4.2	4.3	4.5
Cement	----	2.2	4.4	----
Water	26.9	27.2	26.7	25.9
Mixing Time, min	2.0	4.0	6.0	10
Pelletizer Feed				
Feed Rate, lb/min	ca. 13.4	ca. 13.4	ca. 13.4	ca. 13.4
Water Added, lb				
Pelletization Time, min	ca. 20	ca. 20	ca. 20	ca. 20
Curing Temperature, °F	160-170	160-170	160-170	160-170
Product Properties				
Crush Strength, lb	187±61	181±39	150±46	484±106 (b)
Unit Weight, lb/ft^3				
As-is	58.6	59.2	59.2	54.2
Dry	51.6	49.0	51.0	47.8
Particle Size, wt% pass	Nos. 8/9 (Combined)	Nos. 8/9 (Combined)	Nos. 8/9 (Combined)	Nos. 8/9 (Combined)

(a) Produced by extrusion run

(b) Average of ten measurements with extruded products with lengths of 1.5” to 1.7” and diameter of 1”

Table 2-E-2. Test Conditions and Properties of Pelletized Products Made with SDA Containing Class C Fly Ash from Sunflower Power Holcomb Station in Kansas (Spray Dryer Ash with Class C Fly Ash)

Test Nos. SDA-KS-	**1**	**2**	**3**
Mixer Feed, wt%			
Spray Dryer Ash	76.4	76.4	76.4
Hydrated Lime	4.9	4.9	4.9
Water	18.7	18.7	18.7
Mixing Time, min	4	20.0	20.0
Pelletizer Feed			
Feed Rate, lb/min	ca. 13.4	ca. 13.4	ca. 13.4
Water Added, wt%	0	0	0
Pelletization Time, min	ca. 25	ca. 25	ca. 25
Curing Temperature, □F	160-170	160 - 170	160-170
Product `Properties			
Crush Strength, lb	177±69	221±67	204±56
Unit Weight, lb/ft^3			
As-is	73.4	74.1	74.0
Dry	67.4	67.2	67.6
Particle Size, wt% pass	Nos. 8/9 (Combined)	Nos. 8/9 (Combined)	Nos. 8/9 (Combined)

Determinations of Durability Characteristics of Manufactured Aggregates

The objective of this task is to determine the durability of manufactured aggregates with distinctly different chemical and physical characteristics. The swelling properties and the effects of natural weathering, freeze/thaw and wet/dry treatments on properties of selected manufactured aggregates were determined for comparison.

As described in the previous section, various manufactured aggregates were selected for the durability study. Aggregates used in the durability study included those made from fixated wet FGD materials, spray dryer ash and FBC ash. All aggregates were made from disk pelletization. The crush strength listed below is the average of ten measurements on ca. ½"x3/8" diameter pellets, and is shown as the average ± one standard deviation.

Natural Weathering Treatment.

The durability of aggregate was examined by immersing the aggregate in water and exposed to natural weathering over a period of time Changes in aggregate crush strength were determined periodically as a function of weathering time.

<u>Aggregates from Wet FGD Materials with High and Low LOI Fly Ash.</u> Aggregates made in Test Nos. FGD-LM-PS-3 and FGD-LM-OS-4 were used in the natural weathering durability study for comparison.

In Test No. FGD-LM-PS-3, aggregate was produced from fixated lime wet FGD materials with high LOI fly ash (Reliant Energy Elrama Station). The crush strength decreased from 97±31 lb at 0 day, to 28±8 lb after 84 days weathering and fractured into pieces after 117 days weathering.

In Test No. FGD-LM-OS-4, aggregate was produced from fixated lime wet FGD materials with low LOI fly ash (AEP Gavin Station). The crush strength changed from 232 ±88 lb at 0 days, to 147±37 lb after 117 days weathering, to 110±38 lb after 201 days weathering and to 130±39 lb after 347 days weathering. The aggregate retained over 50% of crush strength after 347 days weathering, whereas the aggregate made in Test No. FGD-LM-PS-3 lost strength completely after 117 days weathering.

It is evident that aggregate made from fixated wet FGD material with low LOI fly ash is more durable than that made from fixated FGD material with high LOI fly ash.

<u>Aggregates from FBC Ash from Low-Sulfur Lignite and High-Sulfur Coal.</u> Aggregates made in Test Nos. FBC-TS-3 and FBC-FS-1 were used in the natural weathering durability study for comparison.

In Test No. FBC-TS-3, aggregate was produced with FBC ash from low-sulfur lignite (New Mexico Power TNP One Station). The crush strength changed from 329± 78 lb at 0 day, to 296±105 lb after 21 days weathering, to 328±108 lb after 44 days weathering and to 260± 68 lb after 155 days weathering. The aggregate retained most of strength after 155 days weathering.

In Test No. FBC-FS-1, aggregate was produced with FBC ash from high-sulfur coal and petcoke (JEA Northside Station). The crush strength changed from 240±80 lb at 0 days, to 204±87 lb at 7 days weathering, to 228±79 lb at 14 days weathering, and fractured to pieces after42 days weathering.

These test results show that aggregate made with FBC ash from low-sulfur lignite was more durable than that made with FBC ash from high-sulfur coal.

Aggregates from FBC Ash with Fly Ash Addition. The effect of fly ash addition on durability of aggregates was evaluated with FBC ash from high-sulfur coal and petcoke (JEA Northside Station).

In Test No. FBC-FS-2, aggregate was produced from the FBC ash with 10% fly ash addition in mix feed (dry basis). The crush strength of aggregate changed from 221±72 lb at 0 day, to 262±127 lb after 7 days weathering, to 372±105 lb after 14 weathering days and to 346±94 lb after 42 days weathering.

In Test No. FBC-FS-3, aggregate was produced from the FBC ash with 30% fly ash addition in mix feed (dry basis). The crush strength of aggregate changed from 348±112 lb at 0 day, to 425±161 lb after 7 days weathering, to 397±179 lb after 14 days weathering and to 323±73 lb after 42 days weathering. In contrast to aggregate from FBC ash without fly ash addition, the aggregate with fly ash addition retained or gain strength after 42 days weathering.

Test results indicate that fly ash addition can improve durability of aggregate made with FBC ash from high-sulfur coal and petcoke.

Aggregates from Spray Dryer Ash Made at Different Mixing Times. Aggregates made in Test Nos. SDA-KS-1 and SDA-KS-3 were used in the natural weathering study for comparison.

In Test No. SDA-KS-1, aggregate was produced from SDA with Class C fly ash (Sunflower Power Holcomb Station) with 4 minutes mixing time. The crush strength decreased from 177±69 lb at 0 day, to 111±50 lb after 11 days weathering and fractured into pieces after 21 days weathering.

In Test No. SDA-KS-3, aggregate was produced from the same mix formulation except that mix time was increased from 4 minutes to 20 minutes. The crush strength decreased from 204±56 lb at 0 day, to 194±60 lb after 21 days weathering, to 141±47 lb after 44 days weathering and to 73±29 lb after 155 days weathering. The aggregate retained over 30% of crush strength after 155 days weathering, whereas the aggregate made in Test No. SDA-KS-1 lost strength completely after 21 days weathering.

Test results show that the durability of aggregate made from SDA with Class C fly ash can be improved with increasing in mix time.

Freeze and Thaw Treatment

The durability of aggregate was examined by immersing the aggregate with ca. ½" x 3/8" diameter pellets in water in a freeze/thaw chamber and exposing them to 15 continuous freeze and thaw cycles (70 ºF/10 ºF) over 5 days. Changes in aggregate crush strength and size gradation were determined periodically over the treatment.

Aggregates from Wet FGD Materials. Aggregates made in Test No. FGD-LS-TS-4 and FGD-LS-FS-4 were used in the freeze/thaw durability study for comparison.

In Test No. FGD-LS-TS-1, aggregate was produced from fixated limestone wet FGD material with Class C fly ash (Reliant Energy Limestone Station). The crush strength decreased from 167±34 lb after 24hr soaking in water, to 176±32 lb after 6 cycles, to 143±79 lb after 11 cycles, and to 94±38 lb after 15 cycles of treatment. The treated aggregate retained 100% +3/8" size gradation. No aggregate degradation was observed after freeze and thaw treatment.

In Test No. FGD-LS-FS-4, aggregate was produced from fixated FGD material with Class F fly ash (Lakeland McIntosh Station). The crush strength decreased from 130±54 lb after 24 hr soaking in water, to 83±19 lb after 6 cycles, to 75±23 lb after 11 cycles and to 69±17 lb after 15 cycles of treatment.

The treated aggregate retained 70% + 3/8" size gradation. Some aggregate degradation was observed after freeze and thaw treatment. Test results show that aggregate made from fixated FGD material with Class C fly ash is more durable than that made from fixated FGD material with Class F fly ash.

Aggregates from Spray Dryer Ash. Aggregates made in Test Nos. SDA-VS-1 and SDA-VS-3 were used in the freeze/thaw durability study for comparison.

In Test No. SDA-VS-1, aggregate was produced from SDA with Class F fly ash (Birchwood Power Station). The crush strength changed from 145±72 lb after 24 hr soaking, to 119±43 lb after 6 cycles, and to 164±41 lb after 15 cycles.

In Test No. SDA-VS-3, the aggregate was produced with the same mix formulation except that 6% of SDA was replaced by cement (dry basis). The crush strength changed from 161±91 lb after 24 hr soaking, to 168±75 lb after 6 cycles and to 134±40 lb after 15 cycles treatment.

In both tests, no aggregate degradation was observed after freeze thaw treatment. Test results show that aggregate made from SDA with Class F fly ash retained strength and size gradation with and without cement addition under freeze and thaw treatment.

Swelling Tests

Swelling Tests were conducted by both Geotechnics and the University of Kentucky. The data sheets showing the results of the swelling tests are located in Appendix A and B. Test results and experimental procedures are discussed below.

Geotechnics. Crushed manufactured aggregate with a size gradation of combined Nos. 8/9 was compacted in a California Bearing Resistance (CBR) mold (6" i.d. and 7" height) for evaluation of swell potential upon wetting in accordance with PTM method 130. The molded sample was submerged in water in a controlled oven at 160±5 °F for a week and then placed in unsubmerged but saturated conditions in the same heated oven to determine the swell potential for an additional week. The percent of swell was monitored by recording the dial reading periodically. As shown in Table 3-A, aggregates made with SDA from Birchwood power station and FBC ash from Tractebel power Red Hills station swelled 0.087% and 0.044% after one week, and 0.022% and 0.044% after two weeks, respectively. Both aggregates had less swelling upon wetting than Haydite (a commercial lightweight aggregate), which swelled 0.22% and 0.17% under the same testing time and conditions. Aggregate made with FBC ash from AES Guayama station (PR-2-Agg) swelled 1.33% after one week and the swell remained at 1.33% after two weeks. With additional treatment, swell of the aggregate (PR-10-Agg) was reduced to 0.14% after one week and remained at 0.14% after two weeks testing. In contrast, aggregate made with FBC ash from JEA Northside station continued to swell from 0.63%, 0.81%, 0.87% and 0.98% after one, two, three and four weeks (see Appendix A). The swelling is related to the continuous hydration of quick lime and anhydrite upon wetting in the high sulfur FBC ash. The ash contained quick lime (CaO) and anhydrite ($CaSO_4$) of 16.5% and 36.8%, respectively. Both hydration reactions can cause expansion (or swelling).

Table 3-A. Swell Properties of Manufactured Aggregates in the Elevated Temperature Test

Aggregate Type	**1 week (a) (% swell)**	**2 weeks (b) (% swell)**
SDA (with Class F fly ash)		
Birchwood Agg. (c)	0.087	0.022
FBC Aggregate (from low sulfur coal)		
PR-2-Agg (d)	1.33	1.33
PR-10-Agg (e)	0.14	0.14
Red Hills Agg (f)	0.044	0.044
FBC Ash (from high sulfur coal/petcoke)		
JEA (g)	0.63	0.81
Commercial Aggregate		
Hyd-Agg (h)	0.22	0.17
Lehigh-lite	0.02	0.02

(a) Submerged in water at 160±5 °F in the first week
(b) Unsubmerged but saturated in water at 160±5 °F in the second week

(c) Aggregate made with SDA from Birchwood power station in Virginia
(d) Aggregate made with FBC ash from AES Guayama station in Puerto Rico
(e) Modified PR-2 aggregate with additional treatment
(f) Aggregate made with FBC ash from Tractebel Power Red Hill station in Mississippi
(g) Aggregate made with FBC ash from JEA Northside station in Florida
(h) Haydite lightweight aggregate

University of Kentucky. The swell tests conducted by the University of Kentucky were similar to those done by Geotechnics, except that the molded samples were submerged in water at ambient temperature. Two tests were conducted with each of two samples using minimum and maximum compaction. In minimum compaction, the aggregate sample was loosed packed in the mold. In maximum compaction, the aggregate sample was compacted in the mold (CBR) by rodding. As shown in Table 3-B, aggregates, made with fixated limestone wet FGD from Lakeland McIntosh station and SDA from Birchwood station had swell of less than 0.1%. Both aggregates had little swelling upon wetting.

Table 3-B. Swell Properties of Manufactured Aggregates in the Ambient Temperature Tests (a)

Aggregate Type	**Max. (% Swell)**	**Min. (% Swell)**
Limestone Wet FGD (Fixated with Class F fly ash) Lakeland aggregate	0.044	0.022
SDA (with Class F fly ash) Birchwood aggregate	0.087	0.087

(a) From May 8, 2002 to May 31, 2002

Determinations of Durability Characteristics of Manufactured Aggregate Products

The objectives of this task are to determine durability properties of aggregate products including concrete masonry units (CMU), asphalt concrete and portland cement concrete made previously with manufactured aggregates in field demonstration. The aggregate product specimens were prepared and subjected to wet/dry, freeze/thaw (with and without immersion in water) cycle treatments. The aggregate products used included those made with lime wet FGD material (fixated with high and low fly ash), limestone wet FGD material (fixated with Class F fly ash) and spray dryer ash (with Class F fly ash) aggregates in field demonstration. The weight and dimension changes of the aggregate product specimens as a function of cycle treatment were determined.

Wet/Dry Cycles Treatment.

The objective is to evaluate the effect of wet/dry cycles treatment on durability of aggregate products. The test specimens were cut and trimmed from concrete masonry units and cement concrete cylinders to the desired dimensions and immersed in water at 70 °F for 24 hr following by drying at 160°F for 24 hr in accordance with procedures in ASTM D-559. Dimensions of the test specimens used are shown in the tables below (0 cycle treatment). The changes in dimensions (length, width and height) and weight were determined after completion of 10, 20, 30, 40 and 50 wet/dry cycle treatments and air dried for three days. Duplicate tests with specimens of slightly different dimensions were conducted for comparison.

Concrete Masonry Units. CMU test specimens were made with lightweight aggregates from limestone wet FGD materials fixated with Class F fly ash (Lakeland McIntosh Station in Florida). The CMU were produced in a block production plant in Florida. Test results follow in Table 4-A-1.

Table 4-A-1. The Effects of Wet/Dry Treatment on Durability of Test Specimens A and B (Limestone Wet FGD with Class F Fly Ash)

Number of Wet/Dry Cycles Treatment	0	10	20	30	40	50
Specimen A						
Dimensions, inch						
Length	7.648	7.647	7.650	7.652	7.655	7.654
Width	2.422	2.423	2.423	2.424	2.424	2.424
Height	1.364	1.367	1.366	1.367	1.367	1.366
Weight, gram	765.8	757.6	758.8	760.1	766.4	768.2
Specimen B						
Dimensions, inch						
Length	7.634	7.635	7.639	7.640	7.643	7.643
Width	2.463	2.466	2.466	2.466	2.466	2.466
Height	1,300	1.294	1.294	1.294	1.294	1.294
Weight, gram	780.4	770.2	771.7	772.7	779.1	781.0

CMU test specimens were made with lightweight aggregate from lime wet FGD materials fixated with low and high LOI fly ash (AEP Conesville Station in Ohio). The CMU were produced in a block production plant in Ohio. Test results follow in Table 4-A-2

Table 4-A-2. The Effects of Wet/Dry Treatment on Durability of Test Specimens A and B (Lime Wet FGD with High and Low LOI Fly Ash)

Number of Wet/Dry Cycles Treatment	0	10	20	30	40	50
Specimen A						
Dimensions, inch						
Length	7.540	7.540	7.544	7.544	7.545	7.542
Width	2.514	2.514	2.514	2.513	2.514	2.514
Height	1.380	1.365	1.364	1.364	1.364	1.316
Weight, gram	679.9	669.7	670.6	670.5	674.9	676.0
Specimen B						
Dimensions, inch						
Length	7.581	7.581	7.585	7.585	7.587	7.585
Width	2.492	2.482	2.484	2.484	2.484	2.484
Height	1.355	1.347	1.341	1.340	1.341	1.341
Weight, gram	742.5	731.7	733.5	734.1	740.7	741.9

CMU test specimens were made with lightweight aggregates from spray dryer ash with Class F fly ash (Birchwood Power Station in Virginia). The CMU were produced in a block production plant in Maryland. Test results follow in Table 4-A-3.

Table 4-A-3. The Effects of Wet/Dry Treatment on Durability of Test Specimens A and B (Spray Dryer Ash with Class F fly ash)

Number of Wet/Dry Cycles Treatment	0	10	20	30	40	50
Specimen A						
Dimension, inch						
Length	7.618	7.618	7.620	7.621	7.622	7.620
Width	2.525	2.522	2.523	2.523	2.523	2.523
Height	1.312	1.311	1.309	1.309	1.308	1.308
Weight, gram	712.8	702.2	703.9	704.5	708.7	711.0
Specimen B						
Dimension, inch						
Length	7.594	7.593	7.595	7.595	7.598	7.564
Width	2.488	2.488	2.486	2.486	2.487	2.488
Height	1.462	1.457	1.457	1.456	1.456	1.456
Weight, gram	684.1	672.2	673.2	673.8	678.1	679.9

Cement Concrete. The cement concrete test specimens used in the wet/dry study were made from two cement concrete cylinders with different mix formulation (mix designs 1 and 2). The cement concrete cylinders were prepared with lightweight aggregate from lime wet FGD materials fixated with low and high LOI fly ash (AEP Conesville Station in Ohio) and they were used in qualification tests for use as lightweight structural concrete[1, 2]. Test results follow in Tables 4-B-1 and 4-B-2

Table 4-B-1. The Effects of Wet/Dry Treatment on Durability of Test Specimens and B FROM MIX DESIGN 1 (Lime Wet FGD with High and Low LOI Fly Ash)

Number of wet/dry Cycles Treatment	0	10	20	30	40	50
Specimen A						
Dimension, inch						
Length	3.000	2.999	2.999	2.999	2.999	2.999
Width	0.969	0.969	0.970	0.970	0.970	0.971
Height	3.046	3.046	3.047	3.047	3.047	3.048
Weight, gram	218.2	217.4	218.3	218.5	220.9	221.6
Specimen B						
Dimension, inch						
Length	2.935	2.935	2.935	2.936	2.936	2.937
Width	0.957	0.957	0.957	0.958	0.958	0.958
Height	3.033	3.034	3.030	3.029	3.030	3.032
Weight, gram	213.0	212.0	212.8	213.1	215.3	215.9

Table 4-B-2. The Effects of Wet/Dry Treatment on Durability of Test Specimens A and B FROM MIX DESIGN 2 (Lime Wet FGD with High and Low LOI Fly Ash)

Number of Wet/dry Cycles Treatment	0	10	20	30	40	50
Specimens A						
Dimension, inch						
Length	2.922	2.923	2.925	2.926	2.927	2.928
Width	1.192	1.195	1.194	1.194	1.194	1.194
Height	2.825	2.829	2.823	2.824	2.825	2.825
Weight, gram	228.1	226.1	227.9	229.5	233.2	234.8
Specimen B						
Dimension, inch						
Length	2.940	2.945	2.945	2.946	2.947	2.948
Width	1.074	1.076	1.078	1.077	1.078	1.078
Height	2.858	2.863	2.865	2.865	2.859	2.861
Weight, gram	209.8	206.9	208.6	209.8	213.1	214.5

From above, little dimension (height, width and length) and weight changes were observed with duplicate test specimens during wet/dry treatments. CMU and cement concrete test specimens made with manufactured lightweight aggregates all had high wet/dry resistance after 50 cycles of treatments. The test specimens were immersed in water during the wet cycle treatment.

Freeze/Thaw Treatment without Immersion in Water.

The objective is to evaluate the effect of freeze/thaw cycles on durability of aggregate products, which were in saturated-surface-dry conditions (SSD) conditions, but not immersed in water. The test specimens were cut and trimmed from concrete masonry units, cement concrete cylinders and asphalt concrete to the desired dimensions and soaked in water for saturation for 48 hours. The saturated specimens were then sealed in plastic bags and frozen at – 6 °F for 24 hr following by thawing at 70°F for 24 hr in accordance with procedures in ASTM D-560. Dimensions of the test specimens are shown in the table below (0 cycle treatment). The changes in dimensions (length, width and height) and weight were determined after completion of 20, 30, 40 and 50 freeze/thaw treatments. Duplicate tests with specimens of slightly different dimensions were conducted for comparison.

Concrete Masonry Units. CMU test specimens were made with lightweight aggregates from limestone wet FGD materials fixated with Class F fly ash (Lakeland McIntosh Station in Florida). The CMU were produced in the block production plant in Florida, as those used in the wet/dry cycles treatment tests. Test results follow in Table 4-C-1.

Table 4-C-1. The Effects of Wet/Dry Treatment on Durability of Test Specimens A and B (Limestone Wet FGD with Class F Fly Ash)

Number of Freeze/Thaw Cycles Treatment	0	20	30	40	50
Specimen A					
Dimension, inch					
Length	7.549	7.553	7.556	7.566	7.557
Width	2.533	2.533	2.531	2.535	2.534
Height	1.525	1.525	1.522	1.525	1.525
Weight, gram	864.5	863.7	863.0	862.1	861.0
Specimen B					
Dimension, inch					
Length	7.534	7.540	7.546	7.546	7.530
Width	2.250	2.251	2.250	2.252	2.253
Height	1.163	1.164	1.160	1.160	1.161
Weight, gram	708.5	707.7	707.0	706.5	705.2

CMU test specimens were made with lightweight aggregate from lime wet FGD materials fixated with low and high LOI (AEP Conesville Station in Ohio). The CMU were produced in the block production plant, as those used in the wet/dry cycles treatment tests. Test results follow in Table 4-C-2

Table 4-C-2. The Effects of Wet/Dry Treatment on Durability of Test Specimens A and B (Lime Wet FGD with High and Low LOI Fly Ash)

Number of Freeze/Thaw Cycles Treatment	0	20	30	40	50
Specimen A					
Dimension, inch					
Length	7.566	7.611	7.618	7.618	7.619
Width	2.526	2.537	2.543	2.543	2.543
Height	1.304	1.320 (a)	1.315 (a)	1.316 (a)	1.316 (a)
Weight, gram	783.0	778.4	775.1	772.9	770.9
Specimen B					
Dimension, inch					
Length	7,589	7.599	7.619	7.602	7.605
Width	2.595	2.602	2.604	2.605	2.605
Height	1.321	1.322	1.323	1.325	1.326
Weight, gram	844.4	842.2	841.8	840.9	839.6

(a) Slightly crumbled

CMU test specimens were made with lightweight aggregate from spray dryer ash with Class F fly ash (Birchwood Power Station in Virginia). The CMU were produced in the block plant in Maryland as those used in the wet/dry cycles treatment test. Test results follow in Table 4-C-3.

Table 4-C-3. The Effects of Wet/Dry Treatment on Durability of Test Specimens A and B (Spray Dryer Ash with Class F Fly Ash)

Number of Freeze/Thaw Cycles Treatment	0	20	30	40	50
Specimen A					
Dimension, inch					
Length	7.635	7.645	7.656	7.660	7.669
Height	2.672	2.670	2.677	2.678	2.683
Width	1.278	1.277	1.284	1.287	1.293
Weight, gram	814.5	813.7	813.2	812.8	811.5
Specimen B					
Dimension, inch					
Length	7.612	7.634	7.642	7.649	7.652
Height	2.529	2.541	2.546	2.551	2.551
Width	1.297	1.303	1.303	1.306	1.306
Weight, gram	794.4	793.6	792.9	792.4	790.8

Cement Concrete. The cement concrete test specimens used in the freeze/thaw study were made from two cement concrete cylinders with different mix formulations (mix design 1 and 2), just as in the wet/dry treatment study. Test results follow in Tables 4-D-1 and 4-D-2

Table 4-D-1. The Effects of Freeze/Thaw Treatment on Durability of Test Specimens A and B from Mix Design 1 (Lime Wet FGD with High and Low LOI Fly Ash)

Number of freeze/thaw Cycles Treatment	0	20	30	40	50
Specimen A					
Dimension, inch					
Length	2.896	2.894	2.894	2.898	2.899
Width	0.951	0.950	0.950	0.952	0.951
Height	3.001	3.001	2.998	3.002	3.005
Weight, gram	222.5	221.5	220.5	219.0	216.8
Specimen B					
Dimension, inch					
Length	3.005	3.011	3.011	3.009	3.012
Width	0.960	0.959	0.959	0.960	0.961
Height	3.039	3.046	3.041	3.043	3.045
Weight, gram	218.2	217.5	216.6	215.5	213.7

Table 4-D-2. The Effects of Freeze/Thaw Treatment on Durability of Test Specimens A and B from Mix Design 2 (Lime Wet FGD with High and Low LOI Fly Ash)

Number of freeze/thaw Cycles Treatment	**0**	**20**	**30**	**40**	**50**
Specimen A					
Dimension, inch					
Length	2.919	2.910	2.920	2.921	2.921
Width	1.127	1.219	1.129	1.130	1.130
Height	2.786	2.784	2..791	2.788	2.786
Weight, gram	230.4	229.3	228.4	227.1	225.4
Specimen B					
Dimension, inch					
Length	2.919	2.919	2.924	2.922	2.920
Width	1.220	1.222	1.222	1.222	1.223
Height	2.831	2.831	2.828	2.834	2.838
Weight, gram	265.7	264.7	264.0	263.2	262.9

Asphalt Concrete. The asphalt concrete test specimens used in the freeze/thaw study were made from three drill core samples from the asphalt pavement demonstrations with manufactured road aggregates in Warren, Ohio, South Park, Pennsylvania and Nokomis Florida (See Summary of Related works). Test results follow in Table 4-E-1, 4-E-2 and 4-E-3.

Table 4-E-1 The Effects of Freeze/Thaw Treatment on Durability of Test Specimens A and B of Drill Core Samples from Asphalt Pavement in Warren, Ohio

Number of Freeze/Thaw Cycles Treatment	**0**	**20**	**30**	**40**	**50**
Specimen A					
Dimension, inch					
Length	2.916	2.915	2.915	2.916	2.912
Width	0.911	0.911	0.911	0.911	0.916
Height	2.966	2.961	2.962	2.961	2.959
Weight	246.7	246.6	246.5	246.5	246.5
Specimen B					
Dimension, inch					
Length	2.893	2.890	2.891	2.896	2.890
Width	0.908	0.908	0.909	0.910	0.909
Height	2.964	2.963	2.963	2.962	2.962
Weight, gram	236.6	236.5	236.5	236.5	236.5

Table 4-E-2 The Effects of Freeze/Thaw Treatment on Durability of Test Specimens A and B of Drill Core samples from Asphalt Pavement in South Park, Pennsylvania.

Number of Freeze/Thaw Cycles Treatment	0	20	30	40	50
Specimen A					
Dimension, inch					
Length	2.836	2.838	2.838	2.837	2.836
Width	0.897	0.896	0.896	0.897	0.897
Height	2.948	2.981	2.945	2.951	2.949
Weight, gram	232.8	232.7	232.7	232.7	232.6
Specimen B					
Dimension, inch					
Length	2.866	2.865	2.865	2.866	2.869
Width	0.902	0.902	0.902	0.904	0.904
Height	2.911	2.910	2.912	2.916	2.916
Weight, gram	236.0	235.9	235.9	235.9	235.8

Table 4-E-3 The Effects of Freeze/Thaw Treatment on Durability of Test Specimens A and B of Drill Core Samples from Asphalt Pavement in Nokomis, Florida

Number of Freeze/Thaw Cycles Treatment	0	20	30	40	50
Specimen A					
Dimension, inch					
Length	2.868	2.867	2.867	2.870	2.869
Width	1.122	1.125	1.122	1.125	1.124
Height	2.819	2.616	2.819	2.820	2.819
Weight, gram	251.6	250.9	250.8	250.8	250.7
Specimen B					
Dimension, inch					
Length	2.818	2.818	2.817	2.820	2.818
Width	1.081	1.083	1.083	1.084	1.083
Height	2.915	2.915	2.915	2.918	2.019
Weight, gram	241.6	241.0	241.0	241.0	240.9

From above, CMU and cement concrete test specimens made with manufactured aggregates from either limestone wet FGD materials or spray dryer ash had high freeze/thaw resistance after 50 cycles of treatment. Little dimension and weight changes were observed during treatments. In comparison, one test specimen made with manufactured aggregates from lime wet FGD materials was slightly crumbled on the surface and lost 1.5% weight after treatment, indicating less freeze/thaw resistance. Both cement and asphalt concrete test specimens made with lime wet FGD materials had high freeze/thaw resistance. The test specimens were in saturated-surface-dry conditions, but not immersed in water. This simulated the natural conditions of freeze/thaw cycles in most applications of CMU and cement concrete in construction.

Freeze/Thaw Treatment with Immersion in Water.

The objective is to evaluate the effect of continuous freeze/thaw cycles treatment on the durability of aggregate products, while immersed in water. The test specimens were cut and trimmed from concrete masonry units and asphalt concrete cylinders to the desired dimensions and immersed in water for 24 hours in a freeze/thaw chamber before testing. The immersed test specimens were then subjected to continuous freeze/thaw cycles treatment (- 4 °F/ 60 °F) in accordance with procedures in ASTM D-666. The analyst recorded the number of the freeze/thaw cycles for test specimens to lose structural integrity.

As shown in Table 4-F-1, CMU test specimens made with manufactured lightweight aggregates from either limestone wet FGD materials or spray dryer ash had medium freeze/thaw resistance after 20 cycles of treatment. Test specimens made with aggregate from lime wet FGD material were degraded after 20 cycles of treatment.

Table 4-F-1 The Effect of Freeze/Thaw Treatment on Durability of CMU Test Specimens

Number of Freeze/Thaw Cycles Treatment	6	10	15	20
Limestone Wet FGD Aggregate (Fixated with Class F fly ash)	good	good	good	slightly spalling
Lime Wet FGD Aggregate (Fixated with low and high LOI fly ash	good	slightly spalling	spalling	spalling and cracking
Spray Dryer Ash Aggregate (With Class F fly ash)	good	good	slightly spalling	slightly spalling

In comparison, test specimens of asphalt concrete made with manufactured aggregate from lime wet FGD materials maintained structural integrity after 200 freeze/thaw cycle treatment indicating high freeze/thaw resistance.

Test results show that immersion in water had a profound effect on the freeze/thaw resistance of CMU made with manufactured lightweight aggregate. Mix designs for aggregate and aggregate products production need to be modified, if simultaneous freeze/thaw at the extreme low temperature (i.e., -4°F) and water immersion cannot be avoided in the application.

Drying Shrinkage Evaluation

The objective is to evaluate shrinkage or expansion properties of combined manufactured aggregate and cement during wet and dry treatments. Excessive interaction of manufactured aggregate with cement could cause drying shrinkage problems in aggregate products. Aggregate in as-is and saturated-surface-dry (SSD) conditions were used in the evaluation. The mixed aggregate and cement were blended with adequate amount of water to produce a mix with a slump of 2” to 3” and then placed in a steel mold (2” x 2” x 11 ¼”) to form a mortar bar for curing, in accordance with procedures in ASTM C157 and C331. The mortar bars were cured in moist conditions (over 95% humidity or immersion in water) and subsequently subjected to drying treatments. Length changes of the mortar bars were measured after drying at 7, 28 and 100 days. The specification for drying shrinkage for lightweight aggregate is 0.1% length change (maximum) in accordance with ASTM C331.

SDA Aggregate. Shrinkage properties of manufactured aggregate, made with SDA from Birchwood power station, were determined in as-is and SSD conditions after drying at 7, 28 and 100 days. As shown in Table 4-G-1, drying shrinkage of SDA aggregate in SSD conditions did not meet the ASTM specification (0.1%, max.). With additive addition, shrinkage of the aggregate was reduced and met the specification.

Table 4-G-1 Drying Shrinkage of SDA Aggregate

	Length Change, % (a)		
	7 days	**28 days**	**100 days**
SDA Aggregate (as-is) (b)			
Bar #1	0.003	0.007	0.026
Bar #2	0.006	0.014	0.026
SDA Aggregate (SSD) (b)			
Bar #1	0.001	0.019	0.132
Bar #2	0.001	0.019	0.129
SDA Aggregate (as-is) (c)			
Bar #1	0.002	0.008	0.029
Bar #2	0,001	0.009	0.028
SDA Aggregate (SSD) (c)			
Bar #1	0.001	0.017	0.035
Bar #2	0.001	0.016	0.034

(a) Shrinkage
(b) Without additive addition in aggregate production
(c) With additive addition in aggregate production

FBC Aggregate Shrinkage properties of manufactured aggregate, made with FBC from AES Guayama station were determined in as-is and SSD conditions after drying for 7, 28 and 100 days, As shown in Table 4-H-1, the mortar bars were expanding instead of shrinking during treatment. Further study is needed to identify the cause of expansion.

Table 4-H-1 Drying Shrinkage of FBC Aggregate

	Length Change, % (a)		
	7 days	**28 days**	**100 days**
FBC Aggregate (as-is)			
Bar #1	0.114	0.342	0.143
Bar #2	0.121	0.285	0.113
FBC Aggregate (SSD)			
Bar #1	0.060	0.104	0.089
Bar #2	0.075	0.117	0.085

(a) Expansion

CONCLUSION

Conclusions appear in the Executive Summary section.

REFERENCES

[1] McCoy, D. C., Wu, M. M., "Demonstration of the Production of Manufactured Aggregates from AEP Gavin and Conesville Station FGD Sludges," Final Report for OCDO Grant Agreement No. CDO/D-98-17, May 31, 2003

[2] Wu, M. M., McCoy, D. C., "Aggregate Production from Lime Wet FGD Sludge," Final Report for OCDO Grant Agreement No. CDO/D-95-2, February 6, 2004

[3] Wu, M. M., McCoy, D. C., Scandrol, R. O., Fenger, M. L., Withum, J. A., Statnick, R. M., "Production of Construction Aggregates from Flue Gas Desulfurization Sludge", DOE Final Report, Cooperative Agreement No. DE-FC26-98FT40027, May 2000.

Appendix A. Swelling Tests - Geotechnics Laboratory

DCN: DS-S33
DATE: 11/14/96
REVISION: 1

Appendix A

geotechnics

ONE DIMENSIONAL SWELL

PTM 130

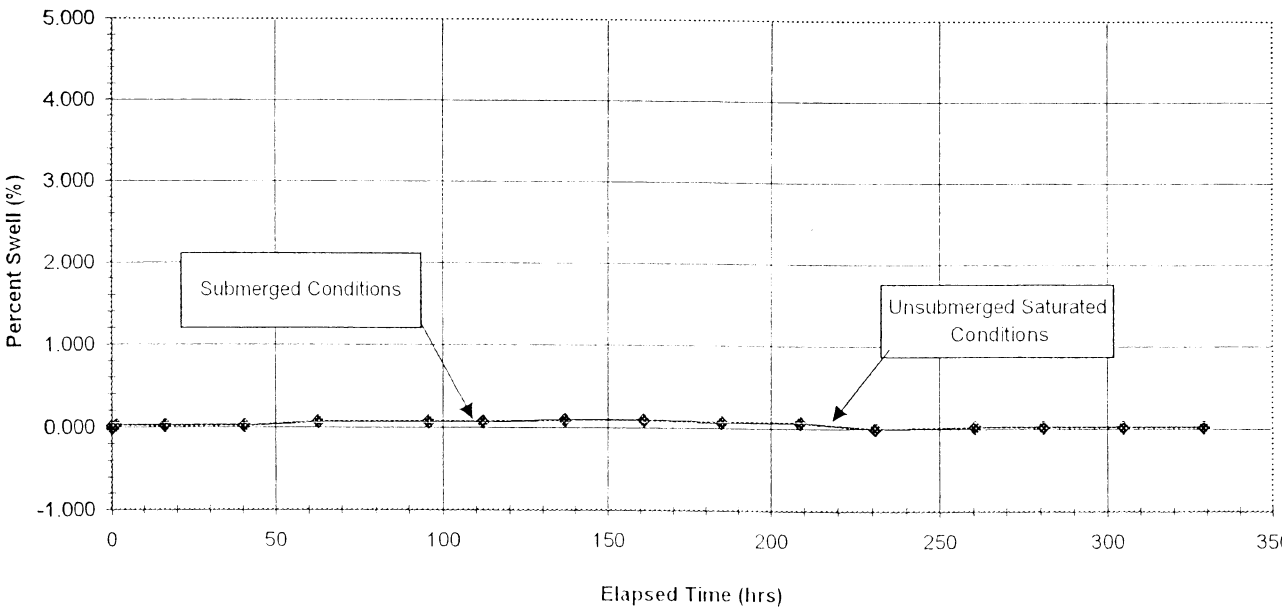
Client	Universal Aggregates	Boring No.	NA
Client Reference	Swell Testing	Depth	NA
Project No.	2002-286-01	Sample No.	Birchwood Agg.
Lab ID	2002-286-01-01	Visual Description	Gray Aggregate

Dial Reading (div)	Percent Swell (%)	Elapsed Time (hrs)	
535	0.000	0	
535	0.000	0.5	
536	0.022	1.5	
536	0.022	16.5	
536	0.022	40.5	
538	0.066	63.0	
538	0.066	96.0	
538	0.066	112.0	
539	0.087	137.0	
539	0.087	161.0	(*)
538	0.066	185.0	
538	0.066	209.0	
535	0.000	231.0	
536	0.022	260.5	
536	0.022	281.0	
536	0.022	305.0	
536	0.022	329.0	

Test Type	***Standard***	***S. Height***	***4.58***
Surcharge (lbs)	***na***	***1 div (in)***	***0.001***

	Initial	Final
Wt. of Mold & WS (gm)	9518	9916
Wt.of Mold (gm)	7130	7130
Wt. of WS	2388	2786
Mold Volume (cc)	2124	2124
Wet Density (gm/cc)	1.12	1.31
Wet Density (pcf)	70.2	81.8
Tare Number	1711	563
Wt. of Tare & WS (gm)	221.35	293.7
Wt. of Tare & DS (gm)	201.87	237.2
Wt. of Tare (gm)	83.54	82.72
Wt. of Water (gm)	19.48	56.5
Wt. of DS (gm)	118.33	154.48
Water Content (%)	**16.5**	**36.6**
Dry Density (pcf)	**60.2**	**59.9**

(*) Sample was removed from the submerged condition after the 166 hour reading.



Tested By JP/DA Date 10/23/02 *Checked By* GU *Date* 11-7-02

Appendix A

DCN: DS-S33
DATE: 11/14/96
REVISION: 1

geotechnics

ONE DIMENSIONAL SWELL

PTM 130

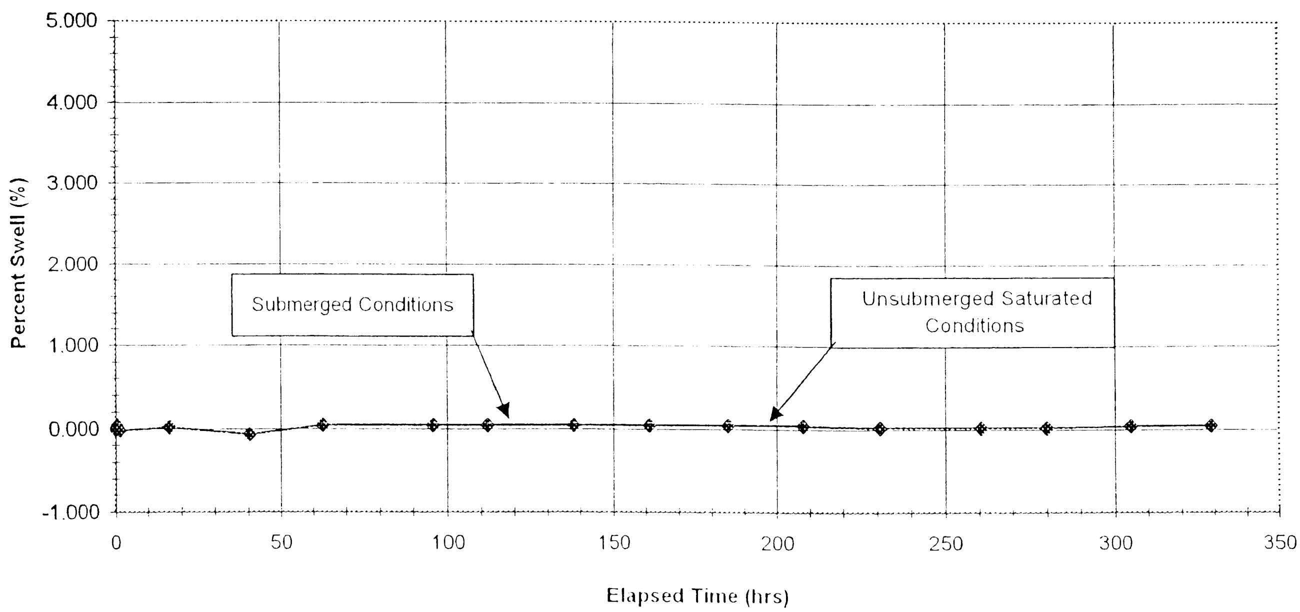
Client	Universal Aggregates	Boring No.	NA
Client Reference	Swell Testing	Depth	NA
Project No.	2002-286-01	Sample No.	Red Hills Agg.
Lab ID	2002-286-01-02	Visual Description	Gray Aggregate

Test Type	***Standard***	***S. Height***	***4.58***
Surcharge (lbs)	***na***	***1 div (in)***	***0.001***

Dial Reading (div)	Percent Swell (%)	Elapsed Time (hrs)
615	0.000	0
617	0.044	0.5
614	-0.022	1.5
616	0.022	16.5
612	-0.066	40.5
617	0.044	63.0
617	0.044	96.0
617	0.044	112.0
617	0.044	138.0
617	0.044	161.0
617	0.044	185.0 (*)
617	0.044	208.0
616	0.022	231.0
616	0.022	260.5
616	0.022	280.0
617	0.044	305.0
617	0.044	329.0

	Initial	Final
Wt. of Mold & WS (gm)	9428	10139
Wt.of Mold (gm)	7120	7120
Wt. of WS	2308	3019
Mold Volume (cc)	2124	2124
Wet Density (gm/cc)	1.09	1.42
Wet Density (pcf)	67.8	88.7
Tare Number	592	1719A
Wt. of Tare & WS (gm)	182.98	374
Wt. of Tare & DS (gm)	173.48	282.91
Wt. of Tare (gm)	81.64	84.8
Wt. of Water (gm)	9.5	91.09
Wt. of DS (gm)	91.84	198.11
Water Content (%)	**10.3**	**46.0**
Dry Density (pcf)	**61.4**	**60.8**

(*) Sample was removed from the submerged condition after the 166 hour reading.



Tested By JP/DA Date 10/23/02 *Checked By* GU *Date* 11/7/02

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DATE: 11/14/96
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ONE DIMENSIONAL SWELL
PTM 130

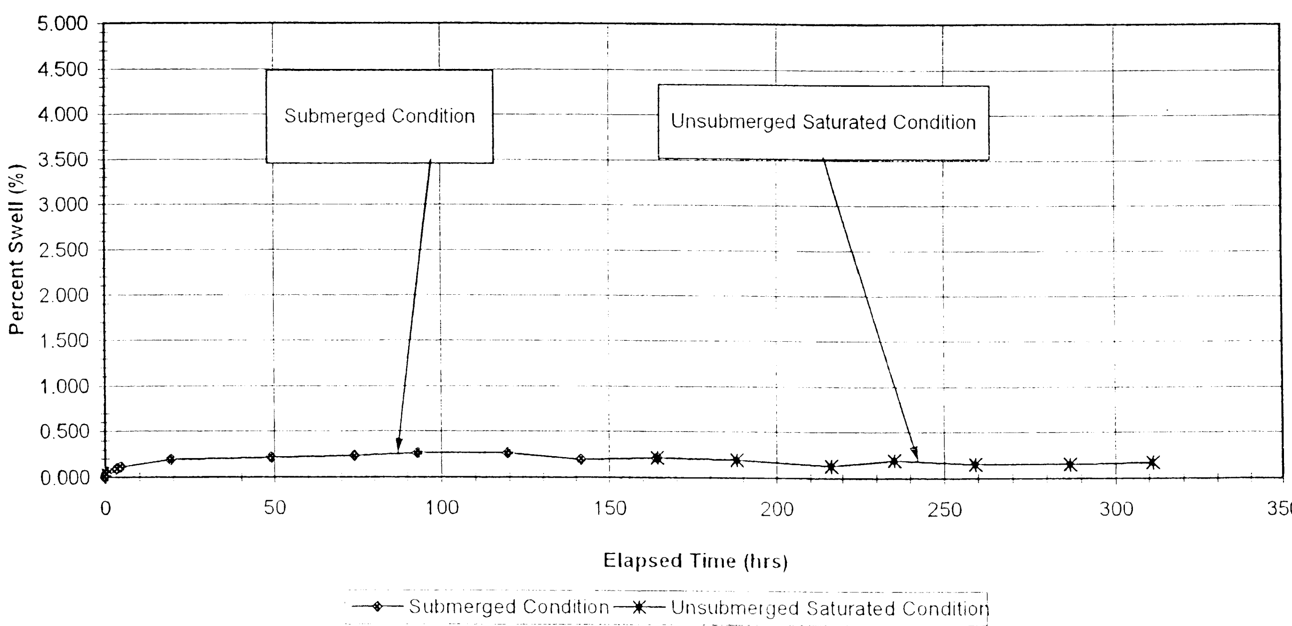
Client	Universal Aggregates	Boring No.	NA
Client Reference	Swell Testing	Depth	NA
Project No.	2002-286-04	Sample No.	HYD-AGG
Lab ID	2002-286-04-01	Visual Description	Brownish Gray Agg.

Test Type	*Standard*	*S. Height*	*4.58*
Surcharge (lbs)	*na*	*1 div (in)*	*0.001*

Dial Reading (div)	Percent Swell (%)	Elapsed Time (hrs)
259	0.00	0
260	0.02	0.1
262	0.07	0.3
262	0.07	0.7
263	0.09	3.1
264	0.11	4.5
268	0.20	19.3
269	0.22	49.1
270	0.24	74.0
271	0.26	93.1
271	0.26	119.8
268	0.20	141.5
269	0.22	164.3 (*)
268	0.20	188.3
265	0.13	216.5
268	0.20	235.3
266	0.15	259.3
266	0.15	286.9
267	0.17	311.0

	Initial	Final
Wt. of Mold & WS (gm)	9293	9958
Wt.of Mold (gm)	7113	7113
Wt. of WS	2180	2845
Mold Volume (cc)	2124	2127
Wet Density (gm/cc)	1.03	1.34
Wet Density (pcf)	64.0	83.5
Tare Number	1122	594
Wt. of Tare & WS (gm)	546.59	388.35
Wt. of Tare & DS (gm)	546.37	318.06
Wt. of Tare (gm)	84.50	81.02
Wt. of Water (gm)	0.22	70.29
Wt. of DS (gm)	461.87	237.04
Water Content (%)	**0.0**	**29.7**
Dry Density (pcf)	**64.0**	**64.4**

(*) Sample was removed from the submerged condition after the 164.3 hour reading.



Tested By JP/DA Date 11/6/02 *Checked By* Jcm *Date* 1-7-03

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Appendix A

PRELIMINARY RESULTS

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ONE DIMENSIONAL SWELL

PTM 130

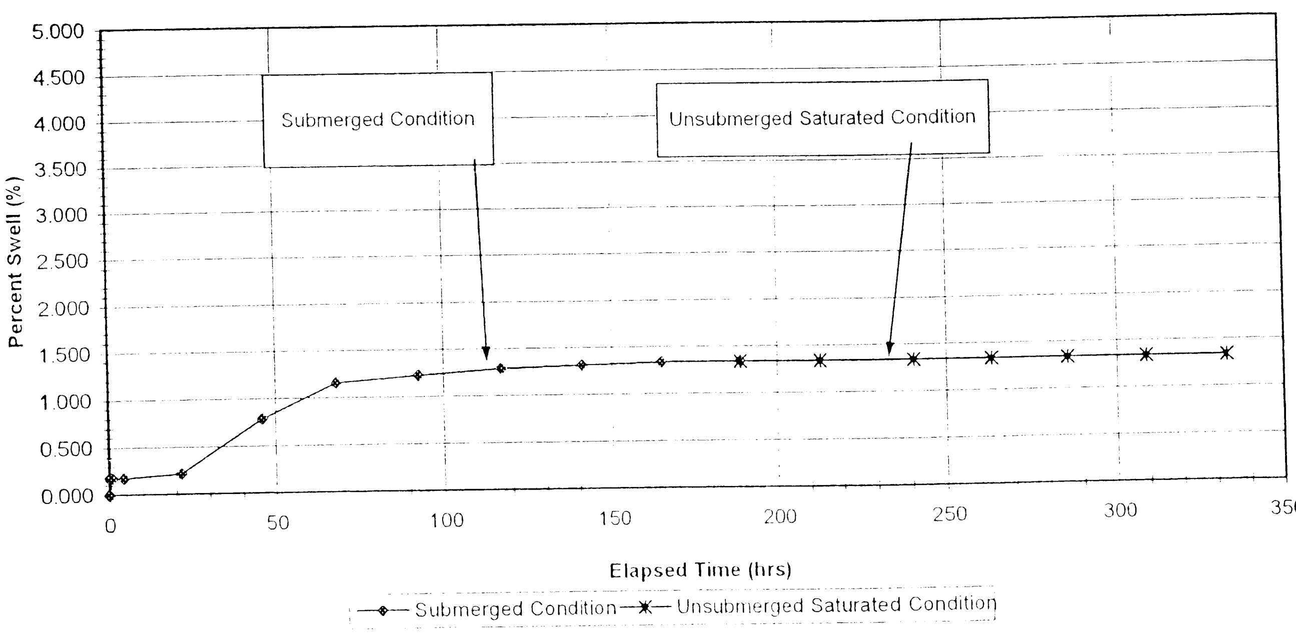
Client	Universal Aggregates	Boring No.	NA
Client Reference	Swell Testing	Depth	NA
Project No.	2003-021-01	Sample No.	PR-2-AGG
Lab ID	2003-021-01-02	Visual Description	Gray Agg.

Test Type	***NA***	*S. Height*	***4.58***
Surcharge (lbs)	*na*	*1 div (in)*	***0.001***

Dial Reading (div)	Percent Swell (%)	Elapsed Time (hrs)	
224	0.00	0	
232	0.17	0.2	
232	0.17	0.6	
232	0.17	1.0	
232	0.17	4.5	
234	0.22	21.5	
260	0.79	46.0	
277	1.16	68.3	
280	1.22	92.8	
283	1.29	117.0	
284	1.31	141.0	
285	1.33	165.0	(*)
285	1.33	189.0	
285	1.33	213.0	
285	1.33	240.4	
285	1.33	263.2	
285	1.33	285.5	
285	1.33	309.0	
285	1.33	333.0	

	Initial	Final
Wt. of Mold & WS (gm)	9877	10435
Wt.of Mold (gm)	7087	7087
Wt. of WS	2790	3348
Mold Volume (cc)	2124	2152
Wet Density (gm/cc)	1.31	1.56
Wet Density (pcf)	82.0	97.1
Tare Number	8	2493
Wt. of Tare & WS (gm)	287.19	1019.4
Wt. of Tare & DS (gm)	255.34	757.4
Wt. of Tare (gm)	73.97	97.49
Wt. of Water (gm)	31.85	262
Wt. of DS (gm)	181.37	659.91
Water Content (%)	**17.6**	**39.7**
Dry Density (pcf)	**69.7**	**69.5**

(*) Sample was removed from the submerged condition after the 165 hour reading.



Tested By JP Date 1/22/03 *Checked By* ... *Date* 2/7/03

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ONE DIMENSIONAL SWELL
PTM 130

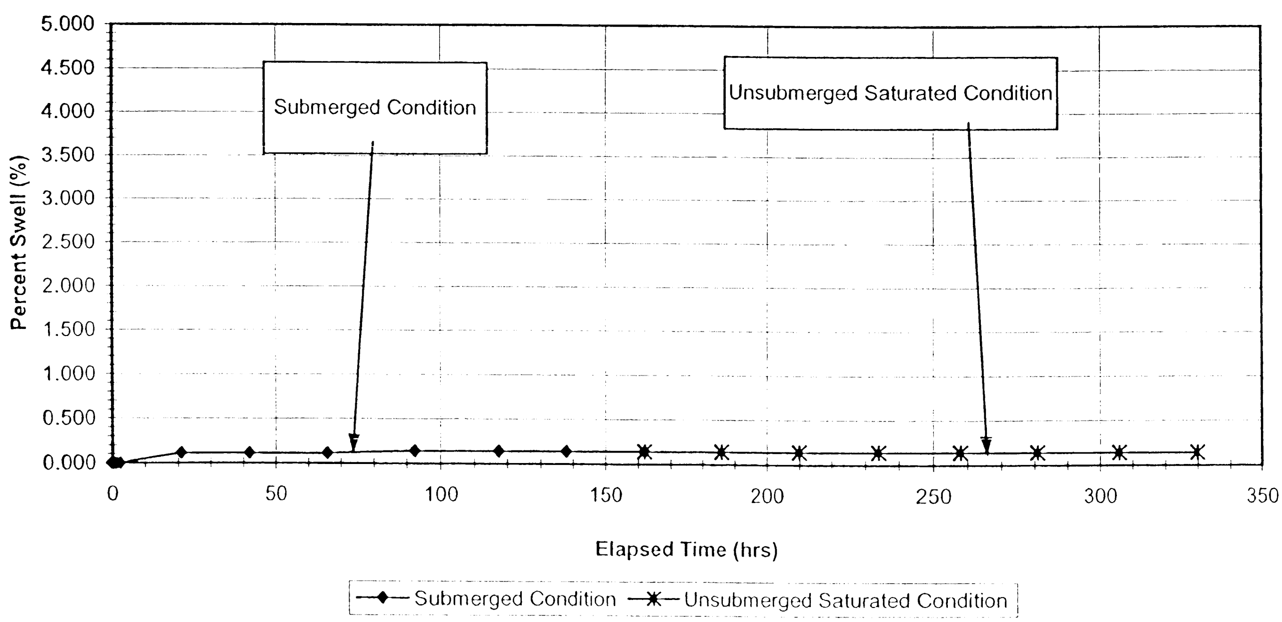
Client	Universal Aggregates	Boring No.	NA
Client Reference	Swell Testing	Depth	NA
Project No.	2003-021-05	Sample No.	PR-AGG-10
Lab ID	2003-021-05-02	Visual Description	Gray Agg.

Test Type	*NA*	***S. Height***	*3.58*
Surcharge (lbs)	*na*	***1 div (in)***	*0.001*

Dial Reading (div)	Percent Swell (%)	Elapsed Time (hrs)	
386	0.00	0	
386	0.00	0.2	
386	0.00	0.4	
386	0.00	1.2	
386	0.00	2.2	
390	0.11	20.9	
390	0.11	41.9	
390	0.11	65.9	
391	0.14	92.4	
391	0.14	117.4	
391	0.14	137.9	
391	0.14	161.9	(*)
391	0.14	185.9	
391	0.14	209.9	
391	0.14	233.9	
391	0.14	257.9	
391	0.14	280.9	
391	0.14	305.9	
391	0.14	329.9	

	Initial	Final
Wt. of Mold & WS (gm)	9116	
Wt.of Mold (gm)	7078	
Wt. of WS	2038	
Mold Volume (cc)	1659	
Wet Density (gm/cc)	1.23	
Wet Density (pcf)	76.7	
Tare Number	A133	
Wt. of Tare & WS (gm)	13.2	
Wt. of Tare & DS (gm)	11.74	
Wt. of Tare (gm)	3.72	
Wt. of Water (gm)	1.46	
Wt. of DS (gm)	8.02	
Water Content (%)	**18.2**	
Dry Density (pcf)	**64.9**	

(*) Sample was removed from the submerged condition after the 161.9 hour reading.



Tested By	JP	Date	6/10/03	*Checked By*		*Date*

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ONE DIMENSIONAL SWELL
PTM 130

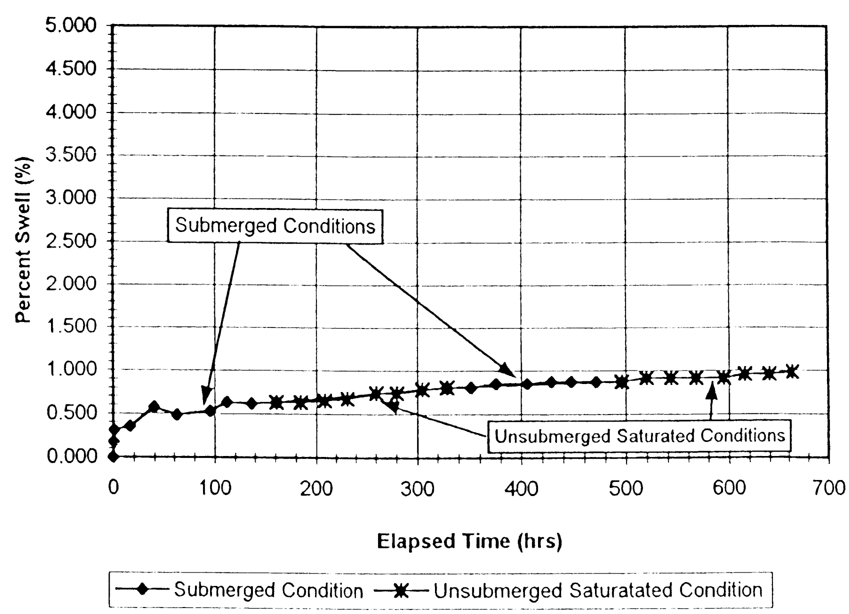
Client	Universal Aggregates	Boring No.	NA
Client Reference	Swell Testing	Depth	NA
Project No.	2002-286-01	Sample No.	JEA
Lab ID	2002-286-01-03	Visual Description	Gray Aggregate

Dial Reading (div)	Percent Swell (%)	Elapsed Time (hrs)	
423	0.00	0	
431	0.17	0.5	
437	0.31	1.5	
439	0.35	16.5	
449	0.57	40.5	
445	0.48	63.0	
447	0.52	96.0	
452	0.63	112.0	
451	0.61	137.0	
452	0.63	161.0	(*)
452	0.63	185.0	
453	0.66	209.0	
454	0.68	231.0	
457	0.74	260.5	
457	0.74	281.0	
459	0.79	305.0	
460	0.81	329.0	
460	0.81	352.0	
462	0.85	376.0	
462	0.85	406.0	
463	0.87	429.0	
463	0.87	448.0	
463	0.87	472.0	
463	0.87	496.0	(*)
465	0.92	520.0	
465	0.92	544.0	
465	0.92	568.0	
465	0.92	594.8	
467	0.96	616.0	
467	0.96	640.0	
468	0.98	664.0	

Test Type	***Standard***		***S. Height***	***4.58***
Surcharge (lbs)	***na***		***1 div (in)***	***0.001***

	Initial	Final
Wt. of Mold & WS (gm)	9689	10175
Wt.of Mold (gm)	7007	7007
Wt. of WS	2682	3168
Mold Volume (cc)	2124	2145
Wet Density (gm/cc)	1.26	1.48
Wet Density (pcf)	78.8	92.2
Tare Number	1713	1131
Wt. of Tare & WS (gm)	222.9	424.3
Wt. of Tare & DS (gm)	209.39	327.4
Wt. of Tare (gm)	83.08	85.19
Wt. of Water (gm)	13.51	96.9
Wt. of DS (gm)	126.31	242.21
Water Content (%)	**10.7**	**40.0**
Dry Density (pcf)	**71.2**	**65.8**

(*) Sample was removed from the submerged condition after the 161 and 496 hour readings.



Tested By	JP/DA	Date	10/23/02	*Checked By*	TLN	*Date*	11-21-02

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ONE DIMENSIONAL SWELL

PTM 130

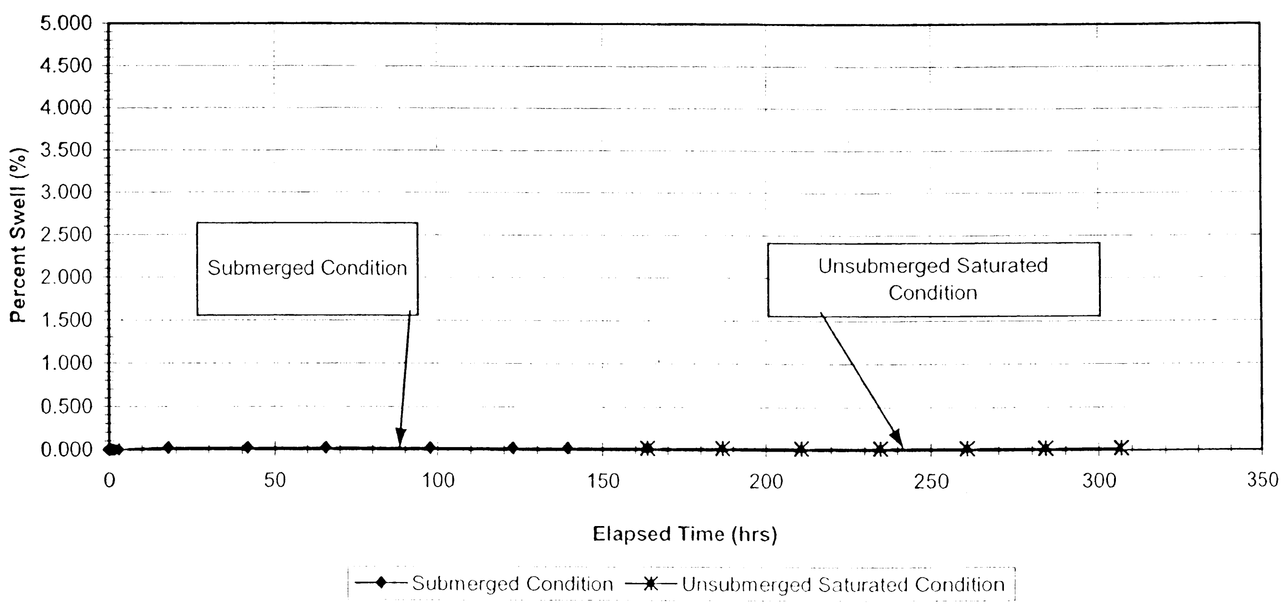
Client	Universal Aggregates	Boring No.	NA
Client Reference	Swell Testing	Depth	NA
Project No.	2002-286-03	Sample No.	LEHIGH-LITE
Lab ID	2002-286-03-02	Visual Description	Gray Aggregate

Test Type	*Standard*	*S. Height*	*4.58*
Surcharge (lbs)	*na*	*1 div (in)*	*0.001*

Dial Reading (div)	Percent Swell (%)	Elapsed Time (hrs)
257	0.00	0
257	0.00	0.5
257	0.00	1.0
257	0.00	1.5
257	0.00	2.8
258	0.02	17.8
258	0.02	41.8
258	0.02	65.8
258	0.02	97.8
258	0.02	122.8
258	0.02	139.3
258	0.02	163.8 (*)
258	0.02	186.8
258	0.02	210.8
258	0.02	234.8
258	0.02	260.8
258	0.02	284.1
258	0.02	306.8
258	0.02	330.8

	Initial	Final
Wt. of Mold & WS (gm)	9183	9744
Wt.of Mold (gm)	7000	7000
Wt. of WS	2183	2744
Mold Volume (cc)	2124	2124
Wet Density (gm/cc)	1.03	1.29
Wet Density (pcf)	64.1	80.6
Tare Number	1708	1691
Wt. of Tare & WS (gm)	360.84	648.2
Wt. of Tare & DS (gm)	341.95	648.2
Wt. of Tare (gm)	83.04	83.58
Wt. of Water (gm)	18.89	0
Wt. of DS (gm)	258.91	564.62
Water Content (%)	**7.3**	**0.0**
Dry Density (pcf)	**59.8**	**80.6**

(*) Sample was removed from the submerged condition after the 163.8 hour reading.



Tested By JP Date 12/3/02 *Checked By* *Date*

Appendix B. Swelling Tests - University of Kentucky Laboratory

Appendix B

Project	Lakeland min
Date	5/8/2002
Operator	TB, BB
Mold #	L1
Mold Tare	16.03 lbs
Surcharge	1095
Sample+Tare	20.97lbs
Soaked +Tare	

Date	Reading	Time	Swell	Temp F	
5/8/2002	0.596	10:10	initial (in.)	67	Percent Swell
5/8/2002	0.596	11:30	0	66	0
5/8/2002	0.596	8:00	0	65	0
5/9/2002	0.594	8:00	-0.002	68	-0.04363
5/13/2002	0.595	8:00	-0.001	65	-0.021815
5/14/2002	0.595	14:30	-0.001	67	-0.021815
5/15/2002	0.595	16:00	-0.001	67	-0.021815
5/20/2002	0.595	10:00	-0.001	67	-0.021815
5/21/2002	0.595	9:00	-0.001	65	-0.021815
5/24/2002	0.595	9:00	-0.001	65	-0.021815
5/28/2002	0.595	10:00	-0.001	65	-0.021815
5/31/2002	0.595	8:00	-0.001	67	-0.021815

Appendix B

Project	Lakeland max
Date	5/8/2002
Operator	TB, BB
Mold #	L2
Mold Tare	16.30 lbs
Surcharge	1191
Sample+Tare	22.41 lbs
Soaked +Tare	

Date	Reading	Time	Swell	Temp F	Percent Swell
5/8/2002	0.539	10:25	initial (in.)	66	
5/8/2002	0.541	11:30	0.002	66	0.04363
5/9/2002	0.541	8:00	0.002	68	0.04363
5/13/2002	0.541	8:00	0.002	65	0.04363
5/14/2002	0.541	14:30	0.002	67	0.04363
5/15/2002	0.541	16:00	0.002	67	0.04363
5/20/2002	0.541	10:00	0.002	67	0.04363
5/21/2002	0.541	9:00	0.002	67	0.04363
5/24/2002	0.541	9:00	0.002	65	0.04363
5/28/2002	0.541	10:00	0.002	65	0.04363
5/31/2002	0.541	8:00	0.002	67	0.04363

Appendix B

Project	Birchwood minimum
Date	5/8/2002
Operator	TB, BB

Mold #	B1
Mold Tare	16.23 lbs
Surcharge	1192 g
Sample+Tare	20.62 lbs
Soaked +Tare	

Date	Reading	Time	Swell	Temp F	Percent Swell
5/8/2002	0.401	9:27	initial (in.)	66	0
5/8/2002	0.397	10:29	-0.004	66	-0.08726
5/8/2002	0.397	11:30	-0.004	67	-0.08726
5/9/2002	0.396	8:00	-0.005	68	-0.109075
5/13/2002	0.396	8:00	-0.005	65	-0.109075
5/14/2002	0.396	14:30	-0.005	67	-0.109075
5/15/2002	0.396	16:00	-0.005	67	-0.109075
5/20/2002	0.396	10:00	-0.005	67	-0.109075
5/21/2002	0.3965	9:00	-0.0045	67	-0.098168
5/24/2002	0.397	9:00	-0.004	65	-0.08726
5/28/2002	0.397	10:00	-0.004	65	-0.08726
5/31/2002	0.397	8:00	-0.004	67	-0.08726

Appendix B

Project	Birchwood maximum
Date	5/8/2002
Operator	TB, BB

Mold #	B2
Mold Tare	16.69lbs
Surcharge	1166g
Sample+Tare	22.07
Soaked +Tare	

Date	Reading	Time	Swell	Temp F	Percent Swell
5/8/2002	0.555	9:29	initial (in.)	66	0
5/8/2002	0.552	10:30	-0.003	66	-0.065445
5/8/2002	0.552	11:30	-0.003	66	-0.065445
5/9/2002	0.552	8:00	-0.003	68	-0.065445
5/13/2002	0.554	8:00	-0.001	65	-0.021815
5/14/2002	0.555	14:30	0	67	0
5/15/2002	0.555	16:00	0	67	0
5/20/2002	0.556	10:00	0.001	67	0.021815
5/21/2002	0.557	9:00	0.002	67	0.04363
5/24/2002	0.557	9:00	0.002	65	0.04363
5/28/2002	0.559	10:00	0.004	65	0.08726
5/31/2002	0.559	8:00	0.004	67	0.08726